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MECHANICS AND TECHNOLOGY OF METAL
AND METAL CERAMIC COMPOSITE MATERIAL PRODUCTS

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MECHANICS AND TECHNOLOGY OF METAL AND METAL CERAMIC COMPOSITE MATERIAL PRODUCTS

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907D0151A Volgograd *MEKHANIKA I TEKNOLOGIYA IZDELIY IZ METALLICHESKIKH I METALLOKERAMICHESKIKH KOMPOZITSIONNYKH MATERIALOV* in Russian 1989 pp 2-215—
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[Book edited by Yu. V. Nemirovskiy, V. A. Kotov, S. M. Barinov and G. A. Krivov, reports presented at National Conference held in Volgograd, 30 May-2 June, 1989]

[Text] **Foreword**

The development and use of composite materials is a priority direction of scientific and technical progress. The use of composites in engineering structures not only significantly improves their operational characteristics, but also in many cases permits the creation of structures which cannot be implemented within the framework of traditional methods. At the present time composites based on plastics have been widely used in various areas of technology. Practical successes in the use of metal-based composites are as yet more modest. However, there is a broad class of engineering problems, the solution of which is impossible without the use of metal composites and metal ceramics. These include primarily the creation of new technology products used under high temperature conditions at high contact pressures, et cetera. The insufficiently broad utilization of metal composites and metal ceramics in technology has resulted from a number of difficulties which arise in the creation of products of these materials and are related primarily to the more complex manufacturing technologies involved, requiring various methods of combining dissimilar materials without causing deterioration in the properties of the components of the composites as they are manufactured. Also rather difficult are the procedures for design of metallic composite products, which require consideration of the properties of reinforcing phases and binders, as well as the properties of the interfaces, the development of optimal design methods. The very broad assortment of metal and metal ceramic composite materials requires that researchers expend great efforts to study the complex of their properties and construct the appropriate mathematical models considering not only structural but also technological factors. Problems relating to joining products made of composite materials are significantly more complex than is true of plastic-based composites. Finally, certain difficulties result from the need to use a combined (system-level) approach in the creation of composites, according to which each element in the process of developing the composite product must be solved in relationship to all other elements. Implementation of this approach in the creation of composite products requires, first of all, good mutual understanding among all specialists participating in the work (designers, technicians, process designers, materials scientists), a well developed method of system-level design and powerful scientific and technical facilities, helping to speed up the process of development of products and improving their quality (automated data bases, expert systems, automatic design systems). The solution of all of these very difficult problems will determine the success of extensive utilization of metallic and metal ceramic composites in technology.

The purpose of the national conference on the mechanics and technology of metal and metal ceramic composite materials, the reports of which are herewith presented for the reader, was to discuss these problems of the creation of products from metallic composite materials and metal ceramics with an audience of composite material technicians, technologists and materials scientists. Most of the reports presented in this collection were given by leading Soviet specialists in the area of composite materials and encompass a broad range of problems: methodology of system-level design of composite material products; methods of calculation, optimization and prediction of properties; the mechanics of composite materials; technologies and technological mechanics of composite materials; problems of the creation of CAD and information management systems for the process of designing composite material products. Many reports follow themes included in the plans for scientific and technical progress of the CEMA member nations up to the year 2000. These materials are important for the development of concepts concerning problems of the creation of machine building products of metal and metal ceramic composite materials and can make a significant contribution to the theory and practice of this problem area. They are of interest both for engineering and technical workers in the area of the mechanics and technology of composite materials, and for specialists developing the new technology.

Academician I. F. Obraztsov

Section I. Problems of Design of Products of Composite Materials

UDC 620.22-419.658.512.2.011.56

SYSTEM-LEVEL AUTOMATED DESIGN METHODOLOGY FOR MACHINE-BUILDING PRODUCTS OF COMPOSITE MATERIALS

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One of the characteristic features of the development of modern human engineering activity is the increasing complexity of the equipment created and the technology of its manufacture, as well as the use in the creation of engineering structures of new materials — usually heterogeneous materials — with the desired combination of physical and mechanical properties. One important variety of heterogeneous materials which has found increasing use in recent years is the metal composite materials, both layer and fiber types, as well as powder metal ceramic composites. The use of these materials in machine-building structures not only significantly improves their usage characteristics, but in many cases allows the creation of products simply impossible to produce with traditional materials.

It is well known that the properties of composite materials depend largely on the manufacturing technology selected; therefore, the development of a technology for the manufacture of composite products is a necessary part of design. Metal and metal ceramic composites are primarily created by solid phase joining methods, among which pulse pressure methods are quite promising. Considering that composites have great anisotropy of properties, their potential can be realized in real structures (parts) if each element is optimally designed for specific conditions of use, and the manufacturing technology selected assures high quality of the composite part with the required strength of joining of the components of the composite. Essentially, the problem of creating products of composite materials with a combination of preselected properties is a complex triple problem of selecting (designing) the internal structure of the composite, the external form of the composite product and the technology of its manufacture. Successful solution of this compound problem is possible only by the use of the systems approach

Composite materials are primarily used to create new or basically new items of equipment, the design of which involves several stages. In the first stage (conceptual design) the general functional structure of the future product and its prospective parameters are selected in accordance with its planned usage conditions. In the second stage the technical assignment is developed and qualitative design of the product to be made of composite materials is performed (selection of type of composite, its components, method of manufacture, construction of mathematical model of the product) by analysis of data on the properties of the components of the composite material, models of the properties of the composite, capabilities of technological implementation, et cetera. In the third stage, detailed parametric design of the composite product is undertaken (the shape of the product is determined, structural and technological parameters of the reinforcement are optimized, the optimal manufacturing technology is developed, the operation of the composite product is modeled and its "correctness" is evaluated, design and manufacturing documentation are produced).

The tremendous volume of information which is processed during design of composite products and the need to use computers to model and optimize composite materials make it desirable to develop an automated system for designing composite material products, requiring the development of computerized tools for this purpose (CAD).

This article analyzes a methodology for system-level automated design of composite material products, implementation of which is illustrated by examples of design of products made of metal layered and fiber composites produced by pulsed pressure, and

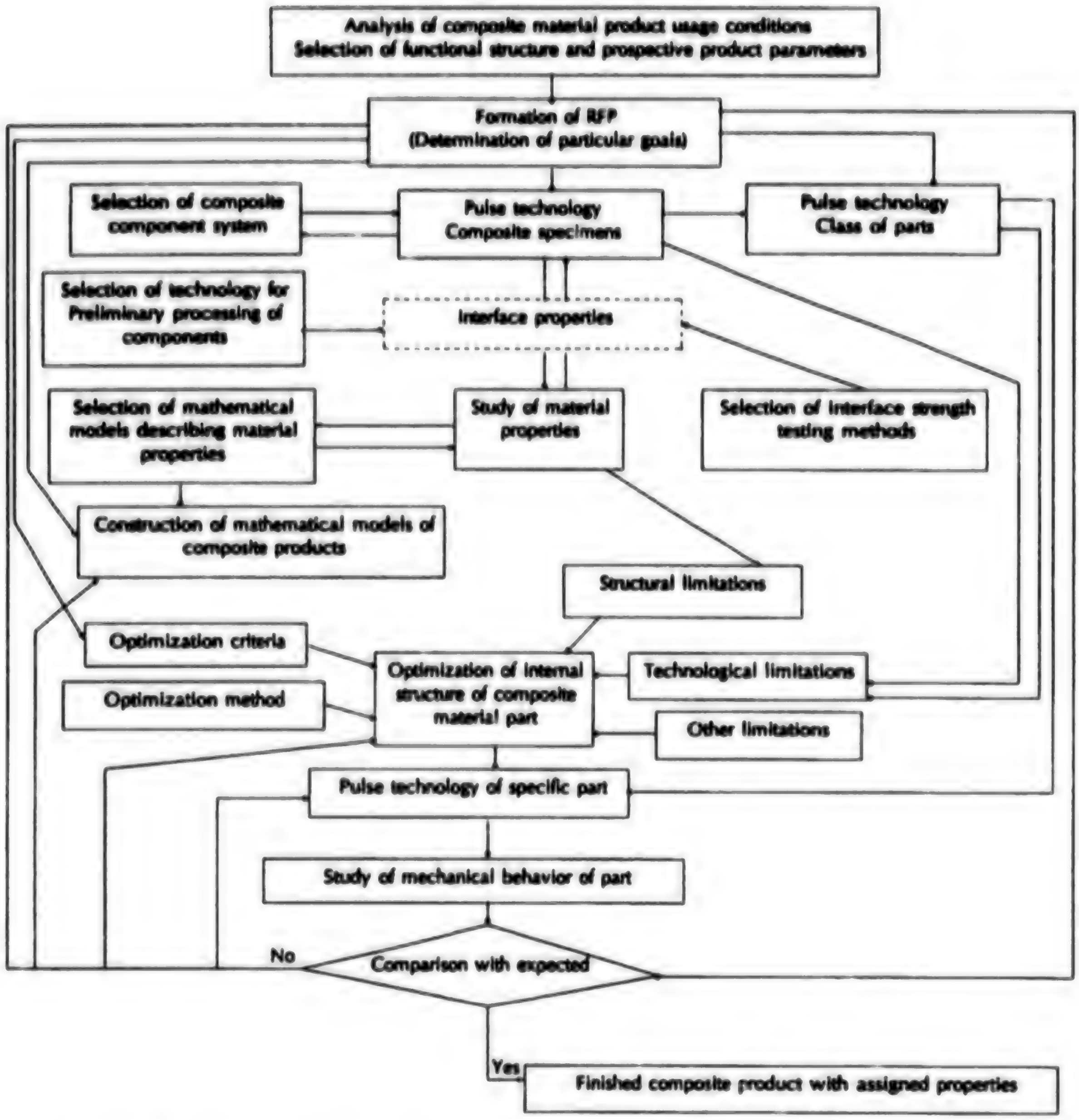

Figure 1. Structural Diagram of Process of Creating Products from Metal Composites by Pulsed-Pressure Methods

also presents a general description of the CAD system which implements the method. The design procedure is formalized as a complex technical system, the input of which receives a vector of specific design goals, while the output carries the vector of desired usage properties of the product, with a four-level hierarchical structure of analysis of the technical system and an adaptive control system. The fourth (highest) level of the hierarchical structure consists of the entire process of design of the composite product. The third level in the hierarchy is formed by the basic procedures making up the process of design and representing its component elements. These are the procedures of construction of the mathematical model of the composite product, optimization of the properties of the product, design of the technology for manufacture of the product from the composite materials which, in turn, may also be formalized as technical systems. The second level in the hierarchy is made up of the individual elements of the procedures in the third level. These

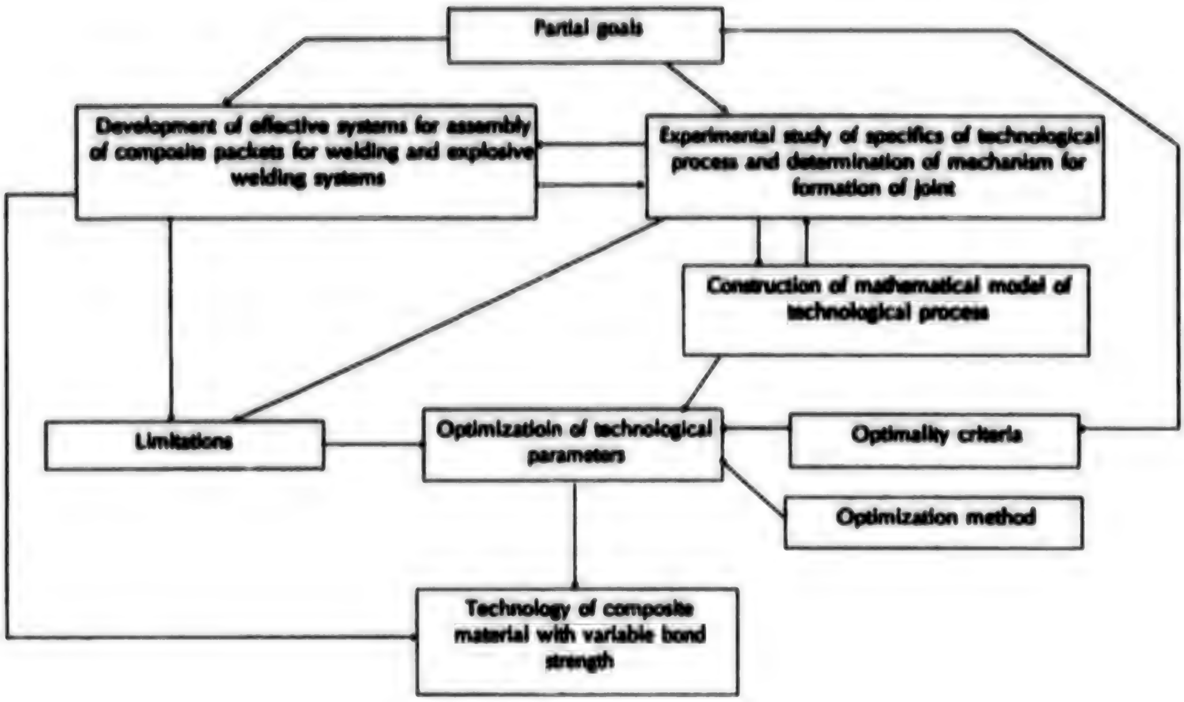

Figure 2. Structural Diagram of Process of Developing Composite Material Pulsed Technologies

include, for example, construction of mathematical models of the properties of the composite material, construction of a mathematical model for the technology of the composite material, et cetera, also formalized as technical systems. The first (lowest) level in the hierarchy consists of elements of the second level components which are considered indivisible. For example, for the procedure of construction of the mathematical model of a composite technology this includes models of elementary standard processes in the technology — ESP (gas-dynamic, kinematic, thermal, deformation, et cetera) which are directly mathematically described, and the local systems which control them. Figures 1-3 show structural diagrams of the four levels of analysis of the technical system and one of the elements of levels 3 and 2 — composite material technology — using the example of creation of products from metal composites by pulsed pressure. This decomposition of the process facilitates construction of a complete mathematical model. Thus, in particular, the mathematical model of the impulse technology can be represented by two parts: mathematical models of individual ESPs plus models of the interactions among them.

The procedure involved in designing a technical system is a process of synthesis, analysis, optimization of the system and manufacture of an experimental specimen. (We note that analysis of a technical system can be performed by formal and informal methods.) A simple example of implementation of system-level design of a composite product is illustrated by Figure 4.

The procedure for system-level design forms the basis of an integrated CAD system for products of metal layered composites (bimetallic sheets, multilayer load-bearing panels, multilayer pipe products) and fiber composites (high-pressure cylinders) and technologies for their manufacture by explosive welding.

The system developed allows: 1) selection of the macrostructure of layered and fiber composites with optimal properties satisfying several optimization criteria; 2) efficient design of sheet and tubular layered and fiber composite structures satisfying the usage conditions; 3) design of a technology for the manufacture of bimetallic and multilayer composites by pulsed pressure.

The basic components of the system are: 1) a data bank of properties of initial composite material components, their costs and types of metallurgical interactions; 2) a data bank of properties of materials used in pulsed metalworking; 3) a bank of mathemat-

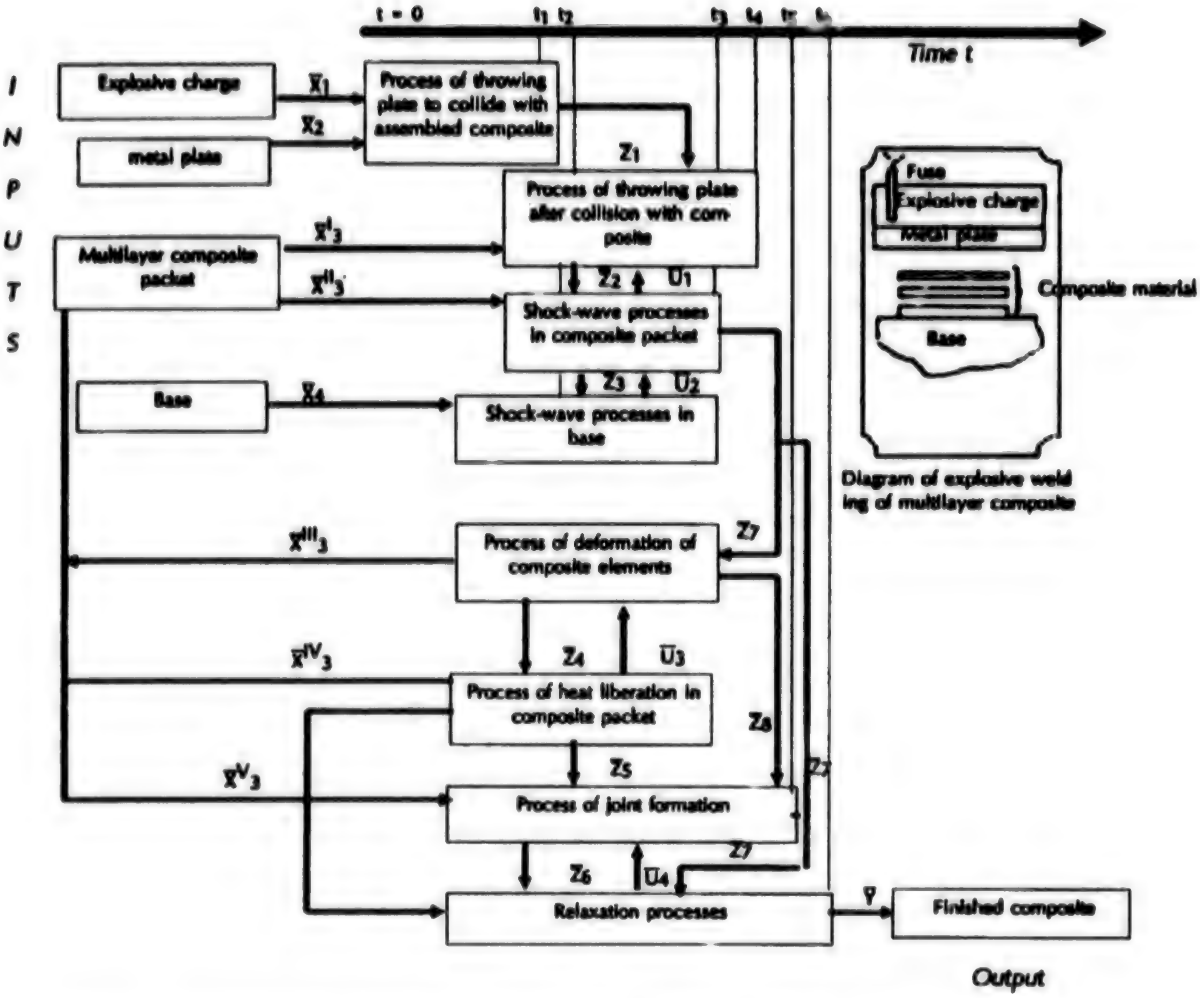

Figure 3. Functional-Time Structure of Process of Explosive Welding of Multilayer Composite Materials

ical models of properties of composites and mathematical models of typical pulsed composite material technologies; 4) a library of CAD programs, including: the programs of the operating system, programs servicing the DBMS [data-base management system], programs for calculation of the properties of composite materials, programs for modeling the stress-strain state of composite material products and their design based on strength criteria, programs for optimizing the properties of composite materials and products made of them and programs for computation and optimization of the parameters of composite material pulsed technologies [2].

In designing products of composite materials, multiple-criterion optimization techniques are used, implemented by the method of probing the space of parameters in dialog mode [3]. Computation of the stress-strain state of composite products is performed by a graphic method of numerical analysis 4. The selection of optimal parameters for a pulsed composite material technology is performed by a system of numerical experimentation implementing versions of calculation 5. Furthermore, the algorithm for automated design includes the operation of selecting metallurgically compatible composite material components.

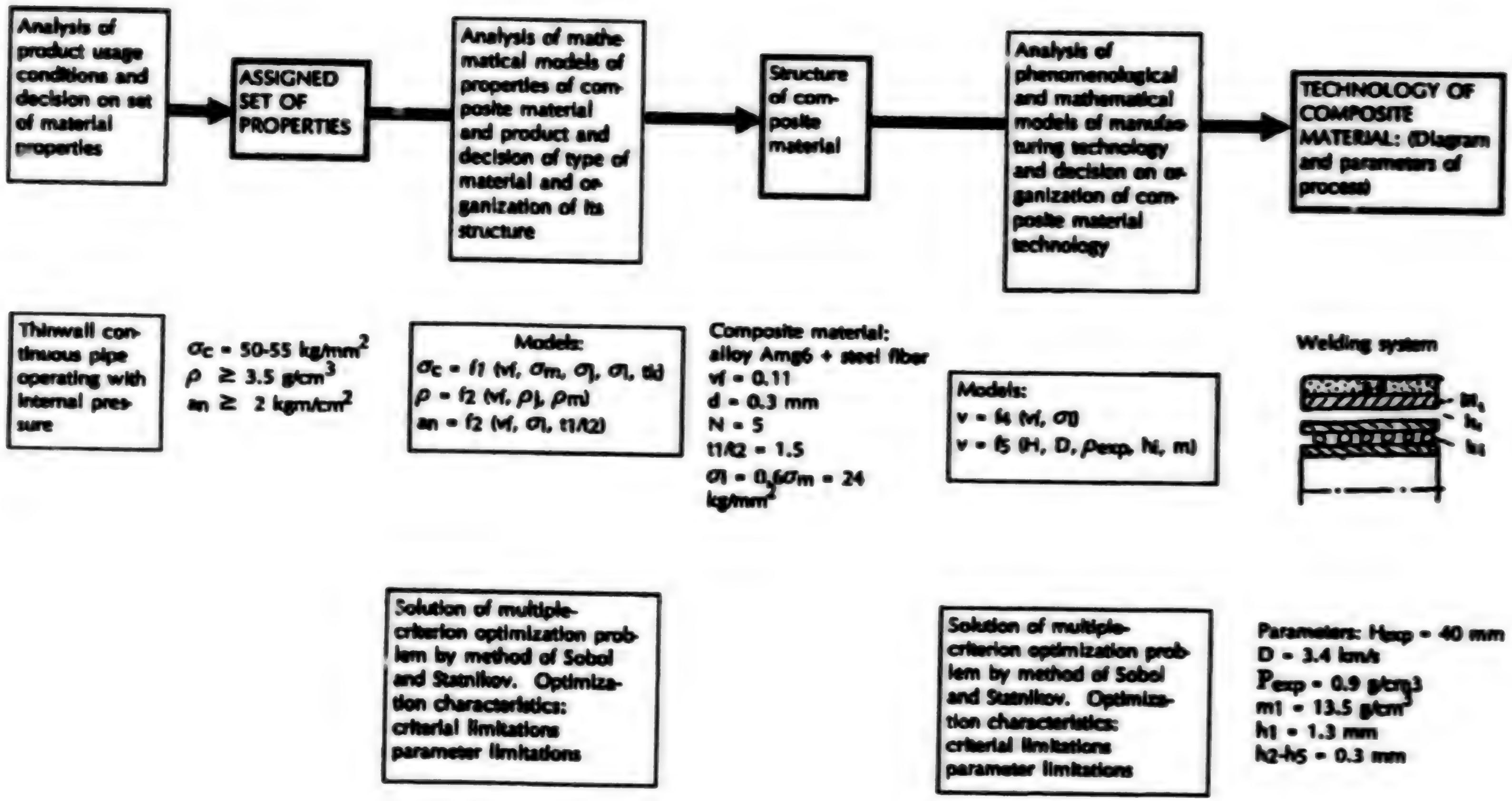

Figure 4. Example: Design of High Pressure Vessel of Multilayer Unidirectional Fiber Composite Material and Process of Its Manufacture by Explosive Welding

The required configuration of computer equipment to implement the CAD system developed is a parallel computer system based on the ES 1035 (and higher) and SM 1420 computers. The programming languages used are FORTRAN-IV and DIAMS-3.

Commercial use of the CAD system developed allows the life cycle of development of composite products, from idea to finished product, to be shortened by a factor of 2-5. The need to perform expensive experimental studies is greatly reduced and the quality of the composite product is improved.

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SPECIFICS OF SYSTEM-LEVEL APPROACH TO DESIGN OF STRUCTURES OF COMPOSITE MATERIAL SEMIFINISHED GOODS

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[Text] The use of semifinished goods consisting of composite materials in products requires the development of a specific system-level design model. It must provide for close information and production interconnection of various groups of designers (materials scientists, product designers, technologists) by a defined hierarchical interrelationship for purposes of generation and analysis of decisions. Thus, the design task is distributed as a hierarchical system of subtasks.

In distributed tasks involving evaluation of the quality of alternatives, it is never possible for the decision makers assigned to the individual subtasks to select a single variant. The result of the performance of the subtasks must therefore be a certain set of alternatives D which are acceptable from the standpoint of the decision makers. The final selection of an optimal version is performed by the decision maker at the level of the entire product. Only the multiplicity of permissible solutions to each subproblem allows the goals of the decision makers to be coordinated both vertically and horizontally, presenting the decision maker at the top with an informative set of permissible product variants for his final selection.

The task of generating the subsets of permissible variants of design and process decisions concerning the structural elements of composite semifinished goods can be represented as follows.

Suppose we are given:

the structure of the design-process decision: structural diagram, type of composite material and version of technology of manufacture of structural element;

the vector of design-process parameters of design-process decision $X^t = (X_1, \ldots, X_m = (q^t|m^t|t^t)$, the components of which correspond to the parameters of the geometry of the structural element, the composite material semifinished product and the technology of manufacturing the structural elements;

the parametric (P) and functional (F) limitations flowing from the external and internal requirements placed on the structural elements;

the vector of design-process decision quality characteristics $f^T = (f_1, \ldots f_k)$.

By a design-process decision variant we shall mean the pair $(xt|ft)$.

Suppose $P_x = \{x_p \in \Pi \mid \Upsilon(x_p) \in \Phi\}$ is the set of prospective design-process parameter variants. Then the set of design-process decision variants can be represented as follows: $P_{x.f} = P_x Px.f = Px \cup Pf$, where $P_f = \{f(x_p) \mid x_p \in P_x\}$ is the set of criterial estimates.

We must find:

the set P_x;

the computation model $f(x)$;

the set $P_{x,\hat{f}}$;

the acceptable criterial boundaries

$$\hat{f}^T = (\hat{f}_1, \ldots, \hat{f}_k);$$

the subset $D \subseteq P_x$, such that $D = D_x \cup D_f$, where

$$D_f = \{f_D \in \hat{f}\} \subseteq P_f, \quad D_x = \{x_D \in P_x \mid f(x_D) \in D_f\} \subseteq P_x.$$

A number of specifics must be considered in solving this problem.

For structural elements of composite material semifinished products, the vector x characteristically has many dimensions and therefore the power of P_x is high. In general, P_x is a subset of dg $\times D_\mu \times D_t$, where D_g, $D\mu$ and D_t are the set of permissible parameters of the geometry, composite material and structural element manufacturing technology, formulated by the designer, materials scientist and technologist based on their "own" quality characteristics f_g, f_μ and f_t. The power of P_x can be reduced by considering the interrelationships among the parameters of the composite material structure and the technological effects capable of damaging the composite semifinished product. The corresponding limitations allow us to decrease the variety of versions which must be evaluated with respect to the usage requirements. The search for these limitations is a complex problem requiring the combined efforts of materials scientists and technologists.

The model of computation of the criterial functions f(x) must be adequate both to the object and to the design purposes. Usually, the process of identify-

ing the object is combined with a process of decision making, transforming the design procedure to a multistage process: from acceptance of simplified, rough models in the initial stages to development of complex and quite precise models in the final stages.

The identification procedure can be represented as:

$$I(P_x, F, Q) = \tilde{f}(x),$$

where F is the set of possible structures $f(x)$, Q are the criteria for adequacy of the model, $\tilde{f}(x)$ is an estimate of the "truth" of the model $f(x)$.

The presence of a model allows information to be generated on the versions of the design-process decision — the set $P_{x,f}$.

The procedure for designating the criterial boundaries $\hat{f}$ requires that additional unformalized information be used, considering the goals and capabilities of the subtask decision makers, interrelated with the data.

This requires use of the dialog mode to generate the boundaries and set D. Suppose $\Pi(P_{x,f})$ is the corresponding dialog procedure. Then the final solution to a problem is the pair

$$(\hat{f}, D) = \Pi(P_{x,f})$$

This solution contains information required for subtasks of lower levels, as well as for combining of variants at higher hierarchical levels.

To implement this approach to the design of structural elements made of composite material semi-finished products it is necessary to organize prospective developments in a certain sequence, directed toward the creation of integrated knowledge bases containing reliable information on structural elements, composite materials, technological processes and the conditions of permissibility of their combination, and also including standard mathematical models allowing the selection of correct design-process decisions in multiple-criterion, distributed product design problems.

The result of these studies consists of procedures for the generation of the set $P_{x,f}$ for standard structural elements, including the set of necessary methods and means for adjustment in specific subproblems, as well as periodic modification of the software and input data. The dialog procedure $\Pi(\cdot)$ is invariant to the design object and can be used in both research and practical problems.

The inclusion of these procedures in the CAD system allows the creation of a system which can not only reduce routine labor of designers, but also form a set of permissible design-process decisions for structural elements and entire products, a necessary condition for optimal design.

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STUDY OF EFFECTIVENESS OF USING FIBER METAL COMPOSITE IN A LOAD-BEARING PANEL

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(Kiev)

The use of composite materials leads to a set of functionally equivalent design-process decisions.

The purpose of this study was to generate permissible design-process decisions and provide a comparative evaluation of the effectiveness of using various materials based on the criteria of minimum mass and cost of a load-bearing panel.

Based on the external and internal requirements placed on the product, we assigned:

- the structural diagram of a unit and its cross sections (Figure 1);
- the type of structural material (fiber composite material — VMKM, D16T, V95 and V120);
- the technology of manufacture of the panel: mechanical working — bending — contact-spot welding.

The procedure for generation and evaluation of the effectiveness of the design-process decisions included the following stages:

1. Assignment of a vector of structural-technological parameters $x^t = (x_1, \ldots, x_m) = (g^t | \mu^t | t^t)$, where g, μ, t are the parameters of the geometry, the composite material and the technology of manufacturing the panel, respectively;

2. Generation of parametric limitations flowing from the structural and process requirements;

3. Generation of functional limitations considering the conditions of usage and manufacture of the product:

$\gamma_1(g, \mu)$ — the strength reserve factor;

$\gamma_2(\mu, t)$ — the bending radius;

4. Generation of the set of prospective design-process decision variants

$P_{x,f} = P_x \cup P_f$, where

$f(x) = (f_1, f_2)$ is the vector of quality characteristics (f_1 is the mass, f_2 is the cost of a panel);

$$P_x = \{ x^T \in \Pi \mid \varphi_{1,2} \in \Phi \}, \quad P_f = \{ f^T(x) \mid x^T \in P_x \},$$

5. The designation of criterial boundaries $\hat{f}_1, \hat{f}_2$ in the process of analysis of prospective design-process decisions $P_{x,f}$ in dialog mode and selection of the corresponding permissible decisions: $D \subseteq P_{x,\hat{f}}$

6. Estimation of effectiveness of the use of various materials was undertaken by construction and comparison of estimated and true curves showing the variation of the decrease in excess panel mass as a function of the corresponding increase in the cost of one kg of the product [1]. The curve obtained is shown in Figure 2, from which it follows that the quality characteristics we analyzed are contradictory and the selection of the optimal design-process decision must be based on an intelligent compromise.

The results of the study led us to the following conclusions:

1. The use of a fiber-metal composite material can achieve significantly greater mass effectiveness than the use of traditional materials while simultaneously increasing the cost of products.

2. For each traditional material there is a certain (critical) level of expediency of using fiber-metal composites as alternatives.

3. Varying the structural parameters of a fiber-metal composite can increase the effectiveness of design-process decisions in comparison to the use of industrially manufactured composite materials.

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OPTIMIZATION OF DESIGN-PROCESS DECISIONS FOR STRUCTURAL ELEMENTS OF COMPOSITE MATERIALS AND THEIR COMBINATIONS

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[Text] Analysis of the prospects for design-process improvement of modern technical products indicates that the search for new design-process decisions by traditional design methods is increasingly difficult due to the continuous increase in complexity of structural and design systems, the use of modern composite materials in load-bearing structures, et cetera.

Successful solution of the problems which arise requires a system-level approach using methods of optimization and the latest in computer equipment.

This article studies problems related to the creation of a dialog optimal decision support system (ODSS). Generation, debugging and testing of an ODSS system was undertaken, selecting a composite sheet material lap joint as a design project. The variables included the parameters of the joint as well as the structural parameters of the materials of the elements being joined.

The ODSS system consists of the following main functional components:

- the DEMON 1 dialog monitor;
- the EPSILON 2 optimization application software package;
- a library of design modules (programs for design of joints, computation of physical and mechanical characteristics of composite materials);
- data bases;
- a knowledge base.

The user of the ODSS is provided with the following capabilities:

- design of joints and material structures in the joint zone;
- management of an archive of known and new design-process decisions for joints and materials;
- generation of queries into the data base and knowledge base;
- generation of estimates of effectiveness in accordance with selected optimization criteria;
- generation of technical documentation.

Implementation of this system required solution of a number of problems related to the creation of the data base and the software system supporting the functioning of the entire system.

A particular position among the system components is occupied by the application software. It includes a library of computation modules containing programs describing the subject area in question.

They include, first of all, programs allowing calculation of the values of the quality criteria:

- the mass of the joint;
- the failure loads under tensile stress through the weakest cross section, where the material is distorted by fasteners, where the material or the fasteners may be broken, at separations in the adhesive layer;
- the cost of manufacture of one running meter of the joint;
- the density of the material of the sheets joined;
- the thickness of the sheets joined.

These programs, combined as required, are used to generate a system of goal functions.

Secondly, there are programs describing the functioning of the object of study and its optimization. They include the following programs:

- a program for calculating the stress-strain state of the joints;
- a program to calculate the strength and rigidity characteristics of the composite material.

These programs are designed to calculate the characteristics which form the required data base for construction of the system of functional limitations and, furthermore, some of them are used in the system of goal functions to compute the values of a number of quality criteria.

These application programs can be used within the framework of the ODSS, together with the optimization program package, as well as independently. This provides the user with full capabilities, since it allows selection of the required operating modes with the system depending on their needs and desires.

The system is the first version and provides the capacity for rather simple organization of its modern-

ization by replacement and (or) inclusion of new software modules, allowing design of broader classes.

The functioning of the ODSS is supported by the use of the programming languages FORTRAN-IV, PL/1, BASIC, as well as the OS YeS operating system, allowing broad utilization.

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UDC 539.3

COORDINATED DESIGN OF COMPOSITES CONSIDERING CHANGES IN LOADING MODE

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The difficult operating conditions of modern machine-building structures place high requirements on the properties of structural materials and their structure. Matching of the fields of stresses, strains and structural parameters of fiber bodies to avoid mixed stress tensor components in the system of coordinates coupled with the fibers and assure that the angles between fibers do not change during deformation allows the construction of matched designs of high-strength, rigid bodies (C-designs), optimized in terms of fiber mass and strength for the loading conditions. It has been shown that similar optimal qualities are provided by matched equal-deformation designs (A-designs), for which the relative fiber deformations are equal for all directions of reinforcement [1-3].

To increase the resistance of a matched body when the conditions of loading change, it is desirable to construct combined designs (K-designs), the structure of which is formed as a combination of the structure of S-designs for various loading conditions. To check the effectiveness of the method of matched design, comparative testing was performed of A-designs, C-designs constructed as the initial approximations of an optimal A-design, designs utilizing a

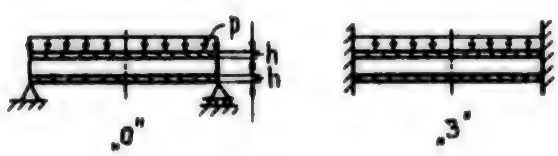

Figure 1.

reinforced material which is homogeneous and orthogonal (P-designs), usually implemented in practice at the present time, and K-designs, intended for use when loading conditions change.

The quality of the designs was compared for flexing freely supported and clamped circular three-layer uniformly loaded plates by comparing the specific strengths of plates of the same shape (Figure 1). By specific strength, we refer to the ratio of intensities of external load P_* corresponding to the beginning of failure of fibers to the mass of fibers M_a of the load-bearing (reinforcing) layer of thickness h.

The loading conditions of the plates were changed by changing their support conditions around the external contour. Instead of a shearing force on the outer contour with free support, a shearing force and bending moment are applied with the contour clamped. The load-bearing layers of the plate K-design were formed as a combination of systems of matched layers taken from A-designs for the case of freely supported and clamped plates. The method of matched design of the structure of the load-bearing layers of the A- and S-plate designs is presented in [1-3]. The technology of manufacture of the three-layer circular plates of a model paper-paraffin?? composite, the method of their bend testing and processing of the experimental results are quite similar to those described in [1].

The heterogeneous structure of the load-bearing layers of the A-designs with variable reinforcing intensity for freely supported and clamped plates is presented in [1]. The structure of the load-bearing layers of the S-designs for plates of various shapes were computed using the condition of constant relative volume of reinforcement at each point in the load-bearing layers in the radial and circumferential directions [2].

Figure 2a, b presents experimental values of the specific strength of plates constructed as implementations of the A-, S-, P- and K-designs. Figure 2c shows the experimental data on the limiting load P_* of these designs related to the limiting load P_{*A} of the A-design of the same outline and with identical reinforcement mass. The symbols of the designs (A, S, P, K) in Figure 2 are marked with the subscript "0" for free support of the plate edges and the "3" for clamped support.

As we can see from Figure 2, the matched A- and S-designs have significantly greater load-bearing capacity for the same reinforcement mass than

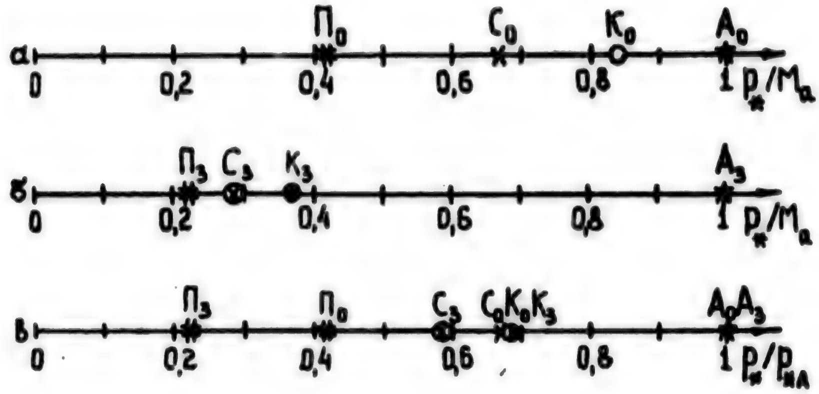

Figure 2

P-designs of the composite material. In particular, the equally deformed designs are stronger than designs of the composite material by more than 2.4-4.4 times. In the case of a design for two loading modes, the combined designs using the reinforcement system described above are 1.6-3 times stronger than designs of composite material.

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UDC 539.3

ONE STOCHASTIC PROBLEM OF DESIGNING MINIMUM WEIGHT COMPOSITE ROD STRUCTURES

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In manufacturing rod structure elements frequently the geometric (rod length) and physical-mechanical (elasticity modulus and strength) characteristics are not achieved with the desired accuracy, corresponding to the accuracy of the calculation model. To assure reliability of a structure it is necessary as it is designed to consider the stochastic nature of the geometric and physical characteristics of the elements of the structure.

In this work, based on assigned distribution functions of the initial parameters, we determine the distribution functions of the output parameters (cross-sectional area of elements).

The following problem of nonlinear programming is solved:

$$\text{minimize} \qquad W(A) \qquad (1)$$

with the limitations

$$z_j^q(A,\Phi) \le \bar{z}_j \qquad j=1,2,\ldots,J_z; \quad q=1,2,\ldots,Q \qquad (2)$$

$$\sigma_i^q(A,\Phi) \le \sigma_i(\Phi_i) \qquad i=1,2,\ldots,N \qquad (3)$$

$$g_{il}(\Phi_i,A_i) < 0 \qquad l=1,2,\ldots,L \qquad (4)$$

Here, W(A) is the goal function (weight of the structure); $A = [A_1, A_2, \ldots, A_N]^T$ is the vector of cross-sectional areas; N is the number of elements in a structure; Q is the number of loading versions. As limitations on stress (3) we use a representation of the phenomenological criteria of strength relative to force P_i^q and cross-sectional area A_i. $\Phi = [\varphi_1, \varphi_2, \times \ldots, \varphi_N]^T$ is the vector of fiber composite winding angles. Equation (2) sets limitations on displacement, where J_z is the number of limitations, $Z_j^q(A, \Phi)$ are the displacements subordinate to limitation J with loading version q, while $\bar{Z}_j$ is the maximum permissible value of this displacement with respect to limited degree of freedom j. Limitations (4) relate to individual elements and define the structural characteristics of the elements, L is the total number of these limitations.

We solve this problem using a multilevel method suggested in [1]. This approach to optimization consists in that in the process of optimization the successive modifications of the structure are performed at three levels:

- at the system level (stage of optimization of geometric characteristics);
- at the level of determination of goal functions of the design variables;
- at the level of elements (in the stage of optimizing the structural characteristics of the materials).

Considering the stochastic nature of the problem, at each iteration at the system level and at the level of an element, the probability is determined of exhausting the load-bearing capacity under various conditions [2].

Recurrent equations were obtained to solve optimization problems at the system level by analysis of only the most disrupted limitation. The problem at the element level is solved by a gradient design method. The necessary conditions were obtained for convergence of the method. An algorithm and

program have been developed for finding the optimal design of minimum weight with the desired probability. The effectiveness of the algorithm and the influence of the stochastic nature of the initial parameters on the optimal design are demonstrated with numerous examples of beam structures.

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UDC 39.3:536.12

PROBLEMS OF OPTIMAL DESIGN OF THERMOELASTIC ANISOTROPIC SHELLS WITH RESIDUAL STRESSES

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Optimal design of the elements of metal structures is usually related to computation of an effective geometric configuration. Recently, the attention of researchers has also been drawn by problems of optimal-stress design of the properties of materials based on their mechanical characteristics and structure.

In this report, primary attention is given to the mathematical statement and solution of problems involving optimization of the stress-strain state of anisotropic metal shells under the influence of a force load under heating conditions by efficient selection of the initial (residual) stresses and strains.

The problem formulated is solved in two stages. In the first stage with assigned heating and force loading functions, conditions are determined which must be satisfied by the residual deformation in order that the summary load will be close to that required. In the second stage, characteristic versions of the implementation of the computed residual deformations are studied, in particular by local annealing or thermoplastic deformation. The initial relations are the equations of thermomechanics and heat conductivity in their quasistatic statement. The variational statement of the problem is used to obtain approximate equations. The optimization criteria accepted are the elastic deformation energy functional and the shape-change energy. Studies are performed for an anisotropic cylindrical shell as a function of its geometric parameters, loading conditions, and distribution of residual deformation. The applied aspects of the results obtained are discussed.

UDC 539.3

APPLICATION OF THE THEORY OF INITIAL SUPERCRITICAL BEHAVIOR IN DESIGN OF BOROALUMINUM SHELLS BY STABILITY CRITERION

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In optimizing shells of composite materials based on the criterion of stability, a material structure is defined which assures the maximum value of critical load parameter λ_c. However, this approach has the shortcoming that the theoretical solutions obtained cannot, generally, be implemented in practice due to the great sensitivity of the shells to imperfections. To eliminate this shortcoming, rational shell designs are selected below by applying the theory of initial supercritical behavior [1], according to which not only the critical load is determined, but also the nature of initial supercritical behavior of shells and their sensitivity to geometric imperfections. Although the basic relationships of this theory are applicable to structures of any anisotropic materials, we shall limit our studies to shells of boroaluminum. For this material, the first problem is that of the form of the physical relationships. It was solved by studying deformation diagrams of unidirectional boroaluminum in extension and compression along and across the fibers.

The experiments showed that in extension and compression along the reinforcement the σ-ε diagrams are linear right up to failure, where the maximum deformation is about 0.65 percent. In extension in the transverse direction, the σ-ε diagram is also linear, the maximum deformation is 0.12 percent, whereas with compression the variation between direction and deformation is nonlinear, and failure occurs at $\varepsilon = 2.5\%$. The essential nonlinearity of the diagram is manifested at $\varepsilon > 1\%$. It follows from this that at small deformations ($\varepsilon < 1\%$) to describe the relationship between stresses and strains in problems of the stability of shells of boroaluminum it is quite justified to use the generalized form of Hooke's law

$$\begin{bmatrix} T \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \cdot \begin{bmatrix} \varepsilon \\ \varkappa \end{bmatrix}, \qquad (1)$$

where T, M are vectors, the components of which are the forces and moments used in the theory of Timoshenko-type shells; ε, $\varkappa$ are the vectors of the corresponding deformations and changes in curvature of the shell; A, B, D are blocks of the rigidity matrix, containing the extension-compression and shear rigidity, the rigidity appearing due to asymmetry of the layered packet, and the bending and twisting rigidity [2]. We shall also write the relationship between deformations ε, $\varkappa$ and displacement vectors $U(u, v, w, \theta, \psi)$ in vector-matrix form.

$$\begin{aligned} \xi &= \xi(u), \\ x &= x(u). \end{aligned} \qquad (2)$$

The variational equation corresponding to the principle of possible displacements considering (1) and (2) becomes

$$\iint_\Omega (T\delta\varepsilon + M\delta\varkappa)\,d\Omega - \lambda \iint_\Omega \Delta'\delta u\,\delta\Omega = 0, \qquad (3)$$

where λ is a parameter proportional to which the load applied to the shell changes, Δ' represents the Frechet derivative of the nonlinear operator Δ.

According to [1] the displacements, deformations and stresses are represented as asymptotic expansions with respect to the powers of the small parameter ξ. For the parameters λ we have the exponential series

$$\lambda = \lambda_c + \xi\lambda_1 + \xi^2\lambda_c + \dots \qquad (4)$$

the coefficients of which represent the critical load and assign the direction of change of the load applied to the shell in the supercritical state. For shells which are closed with respect to one of the coordinates, the coefficient $\lambda_1 = 0$. Therefore, the sign of the coefficient λ_2 defines the nature of the supercritical behavior of shells and their sensitivity to initial imperfections [1]. A method has been developed to compute the critical loads and forms of loss of stability of smooth and reinforced cylindrical shells based on the variational equation

$$\iint_\Omega (T_1\varepsilon_c'\delta u + M_c\varkappa_c'\delta u + T_c\varepsilon_0''u_1\delta u)\,d\Omega - \lambda_c \iint_\Omega \Delta_c'' u_1\delta u\,d\Omega = 0 \qquad (5)$$

of the initial supercritical state by means of the variational equation

$$\iint (T_2 b_0' \delta u + M_1 \varkappa_c' \delta u + T_c b_c'' u_2 \delta u + T_1 b_c'' u_1 \delta u)\, d\Omega - \\ - \lambda_c \iint \Delta_c'' u_2 \delta u \, d\Omega = 0 \tag{6}$$

as well as the coefficient λ_2, which is computed by the equation

$$\lambda_2 = \frac{\iint (2T_1 b_c'' u_2 u_1 + T_2 b_c'' u_1^2)\, d\Omega}{\iint (\frac{1}{\lambda_c} T_c b_c'' u_1^2 - \Delta_c'' u_1^2)\, d\Omega} . \tag{7}$$

Shells of boroaluminum layers with various versions of distribution of the material by layers, various systems of reinforcement and attachment of longitudinal-transverse force sets have been calculated and analyzed. For a five-layer cylindrical shell with the parameters

$\frac{L}{R} = 2;\ \frac{h}{R} = \frac{1}{150};\ t_1 = t_2 = t_4 = t_5 = 0{,}175\,h,\ t_3 = 0{,}3\,h$
and reinforcement angles $\pm\phi$, 0, $\pm\phi$

It has been established that most preferable in terms of critical loads and sensitivity to imperfections are shells with $20° \le \varphi \le 70°$. For structure $\pm\phi$,0,0,0 shells retain high sensitivity throughout the entire range of change of reinforcement angles.

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UDC 539.3:519

OPTIMAL DESIGN OF COMPOSITE MATERIAL PLATES

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We know that plates of composite materials have significantly lower strength properties in the transverse direction than in the longitudinal directions. Therefore, optimal design of such plates must include consideration of transverse shear stress and the normal stress on areas parallel to the middle plane of the plate. Due to this, it is impossible to apply the various refined theories to this situation. This article suggests one method of achieving the goal within the framework of the classical theory of transverse bending of plates. The essence of the method is described below.

The plate being designed is considered to be orthotropic, having the strength peculiarities noted above, while the change in its thickness is considered to be arbitrary. It is assumed that its physical and geometric parameters are such that the classical theory of plate bending is applicable.

The differential equations for equilibrium of a continuous medium, utilizing the surface conditions, lead to certain expressions, the so-called nonbasic stresses τ_{xz}, τ_{yz} and σ_z.

The differential equations for equilibrium of the plate are also obtained in the process, coinciding with the known equation obtained by the traditional method of plate theory, that is the method of analysis of equilibrium of the moments of a differential element in the middle plane. The expressions found for τ_{xz}, τ_{yz} and σ_z, together with the expressions for the basic stresses σ_x, σy and τ_{xy}, are substituted into the strength condition, which for clarity is assumed to be the Mises-Hill condition [2]. It is proven that the strength functional takes on its greatest value either in the middle plane or on the surface of the plate. Considering this factor, an equation is derived for equal plate strength, which, together with the differential equation for equilibrium, forms the solution system for the problem of design of an equal-strength plate. This system, as well as the expression for σ_z is quite cumbersome. The expressions for the stresses τ_{xz} and τ_{yz} are comparatively compact:

$$\tau_{xz} = -\frac{1}{8}(h^2-z^2)\left[B_{11}\frac{\partial^3 W}{\partial x^3} + (B_{12}+2B_{66})\frac{\partial^3 W}{\partial x\,\partial y^2}\right] - \frac{h}{4}\left[\left(B_{11}\frac{\partial^2 W}{\partial x^2} + B_{12}\frac{\partial^2 W}{\partial y^2}\right)\frac{\partial h}{\partial x} + 2B_{66}\frac{\partial^2 W}{\partial x\,\partial y}\frac{\partial h}{\partial y}\right], \tag{1}$$

$$\tau_{yz} = -\frac{1}{8}(h^2-z^2)\left[B_{22}\frac{\partial^3 W}{\partial y^3} + (B_{12}+2B_{66})\frac{\partial^3 W}{\partial x^2\,\partial y}\right] - \frac{h}{4}\left[\left(B_{22}\frac{\partial^2 W}{\partial y^2} + B_{12}\frac{\partial^2 W}{\partial x^2}\right)\frac{\partial h}{\partial y} + 2B_{66}\frac{\partial^2 W}{\partial x\,\partial y}\frac{\partial h}{\partial x}\right].$$

h is the thickness, W is the flexure, B_{ij} are the mechanical characteristics of the plate.

Considering the well-known expressions for the moments M_x, M_y and H, equation (1) can be written as

$$\tau_{xz} = \frac{SN_x}{J} + \frac{h}{4J}\left(1-\frac{Sh}{J}\right)\left(M_x\frac{\partial h}{\partial x} + H\frac{\partial h}{\partial y}\right),$$
$$\tau_{yz} = \frac{SN_y}{J} + \frac{h}{4J}\left(1-\frac{Sh}{J}\right)\left(M_y\frac{\partial h}{\partial y} + H\frac{\partial h}{\partial x}\right), \tag{2}$$

where

$$S = \frac{1}{8}(h^2-z^2), \qquad J = \frac{h^3}{12}; \tag{3}$$

while the transverse forces N_x and N_y are determined by the equations

$$N_x = \frac{\partial M_x}{\partial x} + \frac{\partial H}{\partial y}, \qquad N_y = \frac{\partial M_y}{\partial y} + \frac{\partial H}{\partial x}. \tag{4}$$

Equations (2) represent an extension of the equation of Zhuravskiy to the case of a plate of variable thickness.

All of the problems analyzed above were similarly discussed in cylindrical coordinates. In particular, instead of (2) we obtained the equation

$$\tau_{rz} = \frac{SN_r}{J} + \frac{h}{4J}\left(1-\frac{Sh}{J}\right)\left(M_r\frac{\partial h}{\partial r} + H_{r\theta}\frac{1}{r}\frac{\partial h}{\partial \theta}\right),$$
$$\tau_{\theta z} = \frac{SN_\theta}{J} + \frac{h}{4J}\left(1-\frac{Sh}{J}\right)\left(M_\theta\frac{1}{r}\frac{\partial h}{\partial \theta} + H_{r\theta}\frac{\partial h}{\partial r}\right), \tag{5}$$

where M_z, MF128q and H_zF128q are the moments, while N_z and NF128q are the transverse forces acting per unit length of the middle plane of the plate.

We have also analyzed in detail the case of operation of a plate beyond the limit of elasticity of its material.

At the end of the work as a specific example we study the axisymmetrical task of design of a circular equal-strength plate. A transition is made from the radial coordinate to the new variable ρ

$$r = ce^{-\rho} \tag{6}$$

where c is an unknown constant. This allows the boundary-value problem to be reduced to the Cauchy problem. The behavior of the solutions near the center of the plate $\rho = +\infty$. Integration of the solution system is continued up to a value of the argument ρ_R for which the boundary conditions are satisfied. The constant c is determined by the equation

$$C = Re^{\rho}R \tag{7}$$

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UDC 539.3

DESIGN OF JOINTS IN THINWALL COMPOSITE ELEMENTS

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The design of joints is an important part of the design of structures containing thinwall composite elements. Here we study an algorithm for computation allowing consideration of various technological approaches to the manufacture of such joints, falling naturally within the system of optimal design based on various numerical methods.

1. Computation of contact conditions

Following [1] within the framework of kinematic hypotheses, we obtain based on the variational principle the joining conditions for an arbitrary contact of thinwall elements with arbitrary assignment of kinematic hypotheses for each component. Let us write in abbreviated form the variational principle which applies to the middle surface [1]

$$\iint_{S_0} \tilde{K}_{ji}^{np}\{\vec{R}_i \vec{e}_j\}\,\delta u_{np}\,d\alpha_1 d\alpha_2 + \int_{\delta t} \bar{Q}_i\,\delta a_i = 0 \qquad (1)$$

The following statement applies: the necessary and sufficient conditions for (1) are:

$$\tilde{K}_{ji}^{np}\{\vec{R}_i \vec{e}_j\} = 0 \qquad \int_{\delta t} \bar{Q}_i\,\delta a_i = 0$$
$$\int_{\delta k} \bar{Q}_i^{+}\delta a_i^{+} - \int_{\delta k} Q_i^{-}\delta a_i^{-} = 0 \quad . \qquad (2)$$

Let us first study the univariate case, in which all variables are independent of the coordinate γ_k:

$$\bar{Q}_i^{+}\delta u_i^{+} - Q_i^{-}\delta u_i^{-} = 0 \quad . \qquad (3)$$

Expanding all quantities on the curved coordinate γ_k into functional series:

$$f(\gamma_k, x) = \sum \alpha_i\ \varphi_i(\gamma_k) \qquad (4)$$

the general case can be reduced to the univariate case. However, the variations in (3) are not independent, since due to the kinematic hypotheses accepted concerning their interconnection as coefficients of the expansion of the displacement vector on the normal coordinate at the contact point, we must also accept kinematic hypotheses for continuity of displacement. These equations can be written in the general form:

$$[L^-]\vec{u}^- = [L^+]\vec{u}^+ + \vec{u}_3 \quad , \qquad (5)$$

where $[L^-]$ *and* $[L^+]$ in (5) are matrices with the dimensions $(n^- \times n_c)$ and $(n^+ \times n_c)$, $\vec{U}_3$ is the vector of displacements known at that node, with dimension n_c. Equation (5) imposes n_c constraints on the variations δU_i^+, δU_i^-, which can be represented as the vector $\delta\vec{U}_c$ with dimensions $(n^- + n^+)$:

$$\delta\vec{u}_c = (\delta\vec{u}^-, \delta\vec{u}^+) \quad . \qquad (6)$$

We select in the set δU_{ci} the $n_v = n\text{-}n_c$ independent variations δU_v:

$$\delta\vec{u}_c = (\delta\vec{u}_z, \delta\vec{u}_v) \quad . \qquad (7)$$

Regrouping the n_c equations of (5), we obtain

$$[K_z]\,\vec{u}_z = [M]\,\vec{u}_v + \vec{u}_3 \qquad (8)$$

where the matrices $[K_z]$ and $[M]$ with dimensions $(n_c \times n_c)$, $(n_v \times n_c)$, where K_z is a quadratic matrix. We introduce the symbols

$$\vec{Q}_c = (\bar{Q}^-, -\bar{Q}^+) = (Q_1^-, \ldots, Q_{n^-}^-, Q_1^+, \ldots, -Q_{n^+}^+) . \qquad (9)$$

Equations (3-8) lead to the condition of a joint considering the kinematic hypotheses

$$\vec{Q}_c^{\,T}\cdot[S] = 0 \qquad [L_c]\cdot\vec{u}_c = 0 \qquad (10)$$

Here we have used the symbols

$$[S] = \begin{bmatrix} [E] & 0 \\ [K_z]^{-1} & [M] \end{bmatrix} \qquad [L_c] = \left[[K_z], -[M]\right] \qquad (11)$$

clamping conditions on stress-strain state was studied.

2. Numerical examples

The following problems of longitudinal and transverse deformation of a strip with the left portion clamped and the right portion free, cylindrical flexure of a circular laminated shell with mixed boundary-value conditions at the left end with the right end free from surface loads were studied as numerical examples. The influence of anisotropy of the material and clamping conditions on stress-strain state was studied.

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UDC 621.793.72

DESIGN OF COMPOSITE MATERIAL FOR PLASMA COATINGS AND OPTIMIZATION OF ITS COMPOSITION BY CORRELATION AND REGRESSION ANALYSIS

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Analysis of the specifics of the process of sputtering, study of the structure and properties of coatings and the base metal require the creation of powders for gas-thermal application of coatings for various practical purposes with predetermined characteristics.

In the present case, we set ourselves the task of producing a composite material with the following properties: formation of good-quality coating with preservation of good-quality structure of the base metal, for which purpose the melting point of the coating must fall within the area of hardening temperatures of the base material, giving the coating materials the properties of self-fluxing fluidity, reliable bonding with most structural materials even with the simplest surface preparation, good resistance to oxidation and a broad crystallization interval. The coatings must satisfy the requirements of corrosion resistance and wear resistance.

In selecting the composition and structure of the powder, it is best to use a system-level approach, specifically morphological analysis. The composition of morphological tables allows a broader selection of possible versions to be run through in determining a promising composition. A base material should be selected which meets certain operational requirements, plus supplementary requirements assuring the achievement of a combination of necessary characteristics during application of coatings, thus achieving coating structures such that the coating contains a utectic with low melting point.

Coatings should satisfy the basic principles of design of wear-resistant materials: the structure should be heterogeneous and consist of solid grains uniformly distributed in an elastic-plastic matrix. In this case, the applied load acts primarily on the solid-phase inclusions, with stress relaxation occurring in the matrix. The structure should not change significantly in the friction process. Adhesion bonding should occur between the structural components of the material.

A macroheterogeneous structure can be created by the use of sintering under conditions such that homogenization of the material does not occur.

Thus, the problem consists of selecting the material of the plastic matrix and the strengthening solid phase.

After studying the properties of various components and their effects on each other by means of correlation and regression analysis the optimal ratio in the composition of the composite material was determined. Optimal

selection of components should assure the formation of utectic composites consisting of a plastic matrix with hard boride inclusions. The properties of the

material were studied as functions of the relationship of the components by differential-thermal analysis on a Sinku-Riko temperature-controlled balance and by measurement of microhardness. The experimental

data were used to perform correlation and regression analysis of the relationship among melting point, material hardness (resultant characteristics) and content of chemical elements (factor characteristics).

The experimental results were processed by means of a computer. To determine the variation of the resultant characteristics with the factor characteristics, we solved linear set regression equations such as

$$y_{x_1, x_2, x_3, \ldots, x_n} = a_0 + a_1 x_1 + a_2 x_2 + \ldots + a_n x_n .$$

Selection of the linear form resulted from logical coupling and the correlation fields. As a result, the following values of regression coefficients were obtained, influencing the melting point

$$y_{x_1, x_2, x_3, x_4, x_5, x_6} = 1252{,}1 + 1{,}0416\, x_1 - 4{,}79091\, x_2 - 12{,}474\, x_3 + 9{,}6257\, x_4 - 34{,}317\, x_5 - 0{,}0062\, x_6 .$$

The parameters of these equations indicate the degree of influence of each factor (X_1, X_2, X_3, X_4, X_5, X_6) on the

characteristic analyzed with the values of all other factors fixed. As a factor characteristic was changed by one, the resultant characteristic changed by the value of the coefficient of the corresponding

parameter. The use of this regression equation allows prediction of the melting point. The use of the regression coefficients to select the assigned properties yields near-empirical results. The determination coefficient of 0.97 confirms that the melting point is determined 96% by the composition of the chemical elements.

To determine the variation in hardness with chemical composition and melting point, we solved the set regression equation

$$y_{x_1,x_2,x_3,x_4,x_5,x_6,x_7} = a_0 + a_1 x_1 + a_2 x_2 + \ldots + a_n x_n$$

and obtained the following values of regression coefficients

$$y_{x_1,x_2,x_3,x_4,x_5,x_6,x_7} = -94{,}403 + 1{,}9849 x_1 - 0{,}5826 x_2 - 1{,}8146 x_3 + 2{,}1107 x_4 + 2{,}6441 x_5 + 0{,}2867 x_6 + 0{,}00158 x_7.$$

The paired correlation coefficients computed indicate

$$(R_{yx_1} = 0;\ R_{yx_2} = -0{,}89;\ R_{yx_3} = -0{,}91;\ R_{yx_4} = -0{,}08;\ R_{yx_5} = 0{,}12;\ R_{yx_6} = 0{,}66;\ R_{yx_7} = 0{,}76)$$

the close connection between the resultant and each factor characteristic individually. The set correlation coefficient $R_y = 0.98$ indicates a close connection between the factor characteristics and the haruness of the material.

The determination coefficient $\eta = 0.98$ confirms that the change in hardness of the material is 98% determined by the composition of the elements listed and the melting point.

Composite powders of the optimized composition were prepared by mechanical alloying in a Frich planetary mill with subsequent separation into particle-size fractions by an Alpin air separator. Finely dispersed?? powders were obtained hardened by the boride phase, with the assigned physical and mechanical properties.

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QUALITY CONTROL IN EXPLOSIVELY WELDED METAL COMPOSITES

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The quality of an engineering object is determined by a set of factors which can be combined into the following main groups:

usage (output) properties,

operating conditions,

the set of requirements and preferences of the system creating and utilizing the object,

the status of the internal structure.

Control of the quality of an object begins during its design with the selection of optimal versions of the structure, continues in the process of manufacture by the observation of technological requirements and in the process of use by maintenance of the required status and assurance of suitable external influences. However, all of these stages in the subsequent life of an object must be considered in its design stage.

Considering quality as the degree of suitability of an object from the standpoint of the system (ordering entity) which uses it, the designer must somehow formalize the system of preferences, considering in the process that the preferences themselves may change in the process of design and manufacture of the product.

The method of computing quality developed in the department of applied mathematics of Volgograd Polytechnical Institute has the following distinguishing features.

1. All qualities are measured in a single special scale. Each quantity to be evaluated P_i (property of the object) is converted to a quality fraction by converting its value to the special scale by the use of the function $q_i = q_i(p)$, selected

on the basis of expert estimates. Thus, qualities corresponding to a great variety of properties measured in different scales and units are made comparable, so that they can be numerically compared with each other. The quality q_i is not limited to values in the interval [0, 1], but rather can be assigned, generally speaking, in a positive or negative number. The interval [0, 1] is also used, but qualities within this interval are considered normal, i.e., acceptable and realistic values of the quantities being evaluated. With certain restrictions which we will not discuss here this interval acts as the scale of quality measurement.

2. The quality of an object as a whole (unified criterion) is defined as the mean value of the set of its particular qualities, assuring that the unified criterion falls on the same quality scale. Representations of the class of mean functions convenient for selection of unified criteria and including as particular cases the arithmetic mean, geometric mean and the mean as defined by a. N. Kolmogorov, et cetera, have been developed.

A general form of the unified criterion function is defined by the equation

$$h_1(q)+h_2(q)+\ldots+h_n(q)=h_1(q_1)+h_2(q_2)+\ldots+h_n(q_n)$$

Here the monotonically increasing functions $h_i(q_i)$ define the play of values of the individual particular qualities q_i or more precisely, the derivatives $h_i\ (q_i)$ are proportional to the "weights" $\partial q/\partial q_i$. One promising means for increasing the strength and reliability of structures is the creation of composite products [1].

Based on a classification of heterogeneous bodies according to the nature of the heterogeneity — local, when a typical small element is heterogeneous, or general (large-scale heterogeneity), in which the properties of typical elements differ in different parts of the body, three main types of composite products can be distinguished:

a) compound (composite) parts, in which the elements of the structure consist of several homogeneous parts, joined rather simply into a single whole;

b) parts made of composite materials;

c) one-piece composite structures.

An example of a compound (composite) part is a uniaxially extended plate of duralumin with a central aperture reinforced by a strengthening steel ring welded together by explosive welding (Figure 1). Analysis of the load-bearing capacity of this plate, based on investigation of the stress field and the strength criteria of the structural elements (the material of the plate, the ring and the zone of the joint)[2] indicates effectiveness of increasing the relative thickness of the strengthening ring to ($R_2/R_1 = 1.15$), which leads to a linear increase in the load-bearing capacity of the plate (Figure 2). However, increasing

the thickness of the strengthening ring makes it more difficult to assure good quality welding and increases the mass of the structure, which in many cases is not desirable.

The problem must be solved of selecting the optimal thickness of the strengthening ring, assuring an increase in the load-bearing capacity with the least possible increase in mass of the plate by the introduction of the steel reinforcing ring.

Representing the optimization parameters as $P_1 = R_2/R_1$ and $P_2 = P/P^0_n$ — the relative load-bearing capacity (P^0_n is the load-bearing capacity of the plate without the reinforcement) and converting them to particular qualities by means of the relationships

$q_1 = 10\text{-}1000(P_1\text{-}1)^2$ and $q_2 = 3.31r(0.9P_2)$, we can select the characteristic functions $h_i(q)$ as $h_1 = -e^{-q}$, $h_2 = 2e^q - e^{-q}$, which according to (1) leads to the unified goal function

$$q = \operatorname{arsh} \frac{1}{4}\left(2e^{q_2} - e^{-q_2} - e^{-q_1}\right) \qquad (2)$$

Analysis of the situation demonstrates that in the area of realistic thicknesses of the supporting ring *1* P_1 *1.15* the set of permissible points on the plane (P_1, P_2) is limited above and to the left by the straight line

$$P_2 = 6P_1 - 5 \qquad (3)$$

which expresses the condition of failure of the plate at its boundary with the ring. This line is the Pareto set, which contains points which contains points which cannot be improved (P_1,

P_2).

The output parameter P_1 (relative ring thickness) in this case is also the plate structure control parameter, and therefore substituting into the unified criterion (2) the function (3) we obtain a function of one variable $q = q\ (P_1)$, for which the maximum point is found where $P_1 = 1.09$. We use (3) to compute the optimal value of strength $P_2 = 1.55$. Since the unified quality in this case is $q = 1.12$, we can consider this version of the design to be acceptable.

As a second example, let us study a laminar composite material based on high-strength aluminum alloy V95, obtained by explosive welding and combined rolling. The laminar structure helps to increase the reliability of products by increasing their crack-resistance characteristics. The viability of a product — the capability of the product for use after crack defects appear — depends to a significant extent on the structural parameters of the composite. Comparison of a laminar composite material with its component materials in terms of viability is difficult, since a rather large crack in a homogeneous specimen propagates virtually instantly (zero viability).

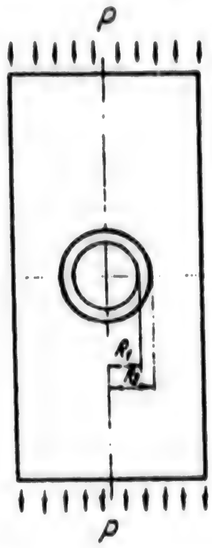

Figure 1. Plate with Reinforced Aperture

Studies of fatigue strength and damping capacity were performed with transverse flexural oscillations of rods in resonant mode using vibrations excited by

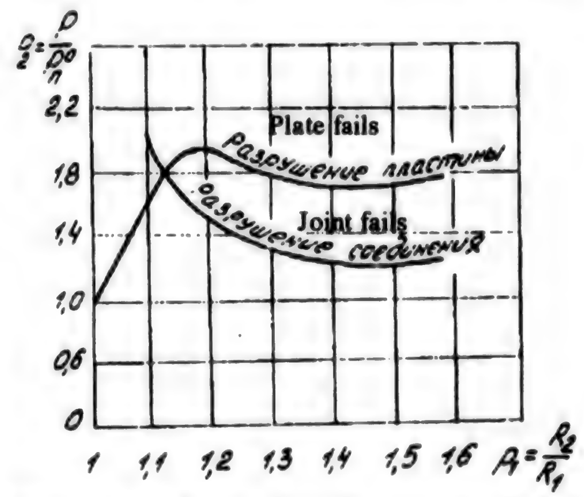

Figure 2. Load-Bearing Capacity of Duralumin Plates Reinforced with Steel Rings

a model KuAI-VV vibration test stand (cf. Table 1 [3]). Analysis of the results obtained leads us to the conclusion that the width of the endurance step representing the viability of the composite depends essentially on the percent content of ADI and achieves its maximum value $\Delta N = 4 \cdot 10^7$ cycles for composite LCM(E) with 17.5% content of the soft interlayer. The method described above was used to construct particular quality functions ($q_i = q_i(P_i)$) *and functions*

Table 1. Testing and Quality Evaluation of 8 mm Laminar Composite Materials

Materials / Parameters	Initial Materials		Content of ADI in Laminated Composite (Layers), %		
	ADI	V95	LCM(C) 4	LCM(D) 11.5	LCM(E) 17.5
Strength, MPa	50-70	150-170	100-110	130-140	100-110
Logarithmic Decrement, %,	1.5-1.7	0.5-0.6	0.6-0.6	1.2-1.5	4.0
Vibration Resistance, MPa	57-102	75-102	60-77	156-210	400-440
Quality	-0.292	0.273	0.092	0.7573	0.837

defining the influence of particular qualities on the quality of the object as a whole.

Calculation of the values of unified quality

$$q = \ln \frac{(4q^* - q) + \sqrt{8 + (4q^* - q)^2}}{2}$$

where

$$q^* = \frac{1}{2} sh(q_1) + \frac{1}{4} q_2 - \frac{1}{4} e^{-q_2}$$

were performed by V. P. Nagibnyy, yielding the results presented in Table 1.

The known vibration-resistance criterion $k = \sigma_{-1}\delta$ [4] is expressed in natural characteristics (cf. penultimate line of table), and therefore its values do not express the degree of acceptability. However, comparison of these values for different materials can yield useful information on the relative qualities of the various materials. Thus, the values of k for composites in the last three columns of Table 1 are related in the same manner as are the values of the criterion k. This fact emphasizes the acceptable similarity of the two quality criteria for laminar materials. However, for pure materials the values of the criterion q were found to be identical, which of course contains no useful information. Comparing laminar composite materials with varying contents of the soft interlayer (LCM(C), (D), (E), it is interesting to note that the increase in the decrement by a factor of three with a slight decrease in endurance resulted in more than doubling vibration resistance k, while the unified criterion q increased slightly, not exceeding the rating of excellent (value of 1). This reflected the relationship among the weights of the particular qualities, in that endurance (in the area of acceptable values of both qualities) was given preference.

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UDC 539.3

ELASTIC-PLASTIC DEFORMATION OF THREE-LAYER SHELLS OF FIBER COMPOSITES

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Thinwall shell structural elements of fiber composites have become increasingly common in modern engineering, making questions of their strength and failure important. In contrast to the traditional method of analysis of the stress-strain state of composite structures, based on the introduction of the averaged characteristics developed in [1], the structural approach allows, in addition to determination of the failure load, determination of the area and the structural elements in which failure occurs. This article analyzes shells consisting of two load-bearing layers of thickness $\delta^{\pm}(x)$, between which is an area of light filler of constant thickness 2H. The load-bearing layers contain $K^{\pm}$ sets of one-dimensional thin fibers in directions which form angles $\alpha_k^{\pm}$ with direction I, K = I,..., $K^{\pm}$ The stresses $\sigma_i^{\pm}$ in the load-bearing layers are determined through the stresses in the binder $\sigma_{o_i}^{\pm}$ and in the sets of reinforcing elements $S_k^{\pm}$:

$$\sigma_{o_i}^{\pm} = \frac{E}{1-(\bar{\mu}^{\pm})^2}(\varepsilon_i^{\pm} + \bar{\mu}^{\pm}\varepsilon_j^{\pm}); \quad S_k^{\pm} = \bar{E}_k^{\pm}[\varepsilon_1^{\pm}(l_{1k}^{\pm})^2 + \varepsilon_2^{\pm}(l_{2k}^{\pm})^2].$$
$$S_{k_i}^{\pm} = S_k^{\pm}(l_{ik}^{\pm})^2; \quad l_{1k}^{\pm} = \cos\alpha_k^{\pm}; \quad l_{2k}^{\pm} = \sin\alpha_k^{\pm}. \tag{1}$$

where $\omega æ_k$ are the individual intensities of the reinforcing filaments. The physical equations of the theory of small elastic-plastic deformations are as follows

$$\sigma_{o_i}^{\pm} = \frac{E}{1-(\bar{\mu}^{\pm})^2}(\varepsilon_i^{\pm} + \bar{\mu}^{\pm}\varepsilon_j^{\pm}); \quad S_k^{\pm} = \bar{E}_k^{\pm}[\varepsilon_1^{\pm}(l_{1k}^{\pm})^2 + \varepsilon_2^{\pm}(l_{2k}^{\pm})^2]. \tag{2}$$

where

$$S_{k_i}^{\pm} = S_k^{\pm}(l_{ik}^{\pm})^2; \quad l_{1k}^{\pm} = \cos\alpha_k^{\pm}; \quad l_{2k}^{\pm} = \sin\alpha_k^{\pm}. \tag{3}$$

The reinforcement parameters are interrelated by the condition of constancy of the cross section of the fibers:

$$z\omega_k^{\pm} l_{1k}^{\pm}\delta^{\pm} = A_k^{\pm} = \mathrm{const}; \quad A_k^{\pm} = z(x_0)\omega_k^{\pm}(x_0) l_{1k}^{\pm}(x_0)\delta^{\pm}(x_0). \tag{4}$$

Considering that the load-bearing layers are in the membrane stress state, while the transverse shear stresses are accepted by the filler, we obtain for the forces and moments

$$T_i = \delta^{+}\sigma_i^{+} + \delta^{-}\sigma_i^{-}; \quad M_i = H(\sigma_i^{+}\delta^{+} - \sigma_i^{-}\delta^{-}). \tag{5}$$

After exclusion, considering equations (1)-(5), of tangential force T_2 and moment M_2 from the equations of the theory of thin shells, we obtain the solution system

$$\bar{y}' = \bar{f}(x, \bar{y}, \bar{p}), \quad \bar{g}(x_0, x_1, Q) = 0, \tag{6}$$

where $\vec{Q}$, $\vec{\rho}$ are parameters included in the right parts of the differential equations and the boundary-value conditions, respectively. The problem is to find the function $\vec{\rho}$, ($\vec{Q}$), defining the values of $\vec{\rho}$ and $\vec{Q}$ for which in one of the structural elements of the shell either plastic flow starts or plastic rupture occurs, i.e., one of the static strength criteria is met:

$$\max_x [(\sigma_{o_1}^{\pm})^2 - \sigma_{o_1}^{\pm}\sigma_{o_2}^{\pm} + (\sigma_{o_2}^{\pm})^2] = (\sigma_*^{\pm})^2, \tag{7}$$

$$\max_x |S_k^{\pm}| = S_{*k}^{\pm}, \tag{8}$$

where $\sigma_*^{\pm}$, $\sigma_{*_k}^{\pm}$ is either the elastic limit or the failure stress.

A program for numerical solution of this problem was written in Fortran-77, implementing the methods of variable elasticity parameters to solve problems of elastic-plastic deformation and the method of spline colocation to solve the boundary-value problems (6). Calculations were performed on a YeS-1061 computer.

As an example, let us present the results of solving the problem of constructing failure surfaces of three-layer cylindrical and conical shells under the influence of uniform internal pressure $q_1 = 0$, $q_n = p$. The edge of the shell x = 0 is rigidly clamped u(0) = w(0) = θ(0) = 0, while at edge $x = L/\sqrt{RH} = l$ the conditions $T_1(l) = M_1(l) = 0$, $N_1(l) = Q$, i.e., $\vec{p} = p$, $\vec{Q} = Q$. Calculations were performed with the

following values of the problem parameters: $K^{\pm} = 2$, $l = 10$, δ ? $R = 10^{-3}$, $\alpha_1^{\pm} = 0.25\Pi$, $\sqrt{R/H} =$ $\alpha_2^{\pm} = 0.75\Pi$, 5, $\omega_k^{\pm}(0) = 0.3$. The binder material was aluminum, the reinforcing fibers were made of steel. The figure shows the surfaces of the initial and plastic failure for a cylindrical (dot-dash line) and conical ($\gamma = 45°$ solid line, $\gamma = 67.5°$ dash line) shells. The failure surfaces consist of three sections: where $-p_1 \leq p \leq p_2$ failure occurs in the internal load-bearing layer at the point of application of the shear force to the binder material. As the absolute intensity of surface load increases, the failure mode changes: failure occurs in the outer load-bearing layer at the clamping point. Calculations show that the mechanisms of initial and plastic failure may not coincide either in the coordinate of the corresponding cross section or in the structural element. The specific values of failure parameters depend essentially both on the physical-mechanical properties of the component elements of the composite and on the geometric dimensions of the shell. We note that an increase in the quantity of reinforcing material does not always lead to an increase in the strength of the entire structure. It can be demonstrated that if the relationship of Young's modulus of the materials of the binder and reinforcement is less than a certain value, the strength of the structure will decrease with increasing quantity of reinforcing material.

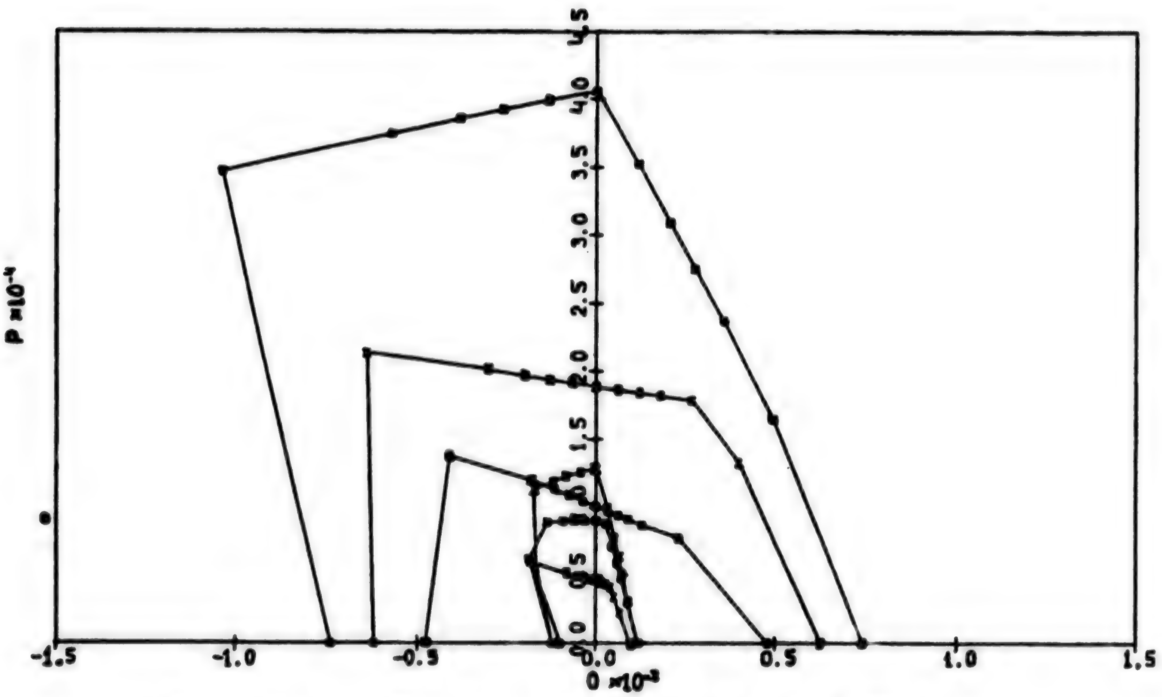

Figure. Initial and Plastic Fracture Surfaces cI, aI, kz, L=10, Hn=5

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UDC 539.3

METHOD OF COMPUTATION AND RATIONAL DESIGN OF COMPOSITE SHELLS FOR SHORT-TERM LOADS

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Problems of damping, strength, stability and optimal design of composite thinwall structures are attracting many researchers today. Such structures, experiencing both static and dynamic external influences, are widely used in a great variety of areas of machine building, in the aviation, space, ship building and many other branches of industry.

When methods are developed for the design of structural elements of composite materials, the mathematical formulation of the problems involved must reflect the characteristic features of the deformation of the material, which may significantly influence its load-bearing capacity. Traditional design models, when applied to composite structures, often lead to inaccurate conclusions concerning their usage properties.

This article suggests a version of a calculation model describing deformation (including dynamic deformation) of smooth layered composite shells considering Karman-type geometric nonlinearity, shear deformation through the height of the entire packet, structural anisotropy of individual layers and their interactions. Versions of the theory of single-layer shells and thinwall reinforced shells, including the "classical" theory, are particular cases which follow from the initial solution equations.

The model suggested is used to study the bulging of cylindrical three-layer shells and determine the specifics of their supercritical behavior under aperiodic short-term loads, static loads of various types for reinforced and smooth shells made of a composite fiber polymer- or metal-based material. Specific numerical solutions are presented for the corresponding problems over a broad range of physical and geometric parameters of the shells. It is shown that the postcritical behavior of the shells depends on the rigidity characteristics of the layers, their mutual placement, wave formation and the forms of loading during various time stages. Furthermore, due to the control of these characteristics of a layered shell, this single program also solves the problem of defining rational structures for an assigned load spectrum and maximizing loads while retaining the assigned shell mass.

The problem of flow of a supersonic gas stream around a cylindrical three-layered shell of constant thickness is also studied. An equation is derived for the critical flutter rate as a function of the geometry of the shell and structure of the reinforcement. Methods are found for distributing rigidity through the shell in order to increase the critical rate causing oscillation.

UDC 539.3

SPECIFICS OF FAILURE OF METAL-CERAMIC PANELS

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Let us study a two-layer smooth shell, rectangular in plan, bent by uniformly distributed pressure of intensity P. We shall introduce the curved system of coordinates x_1, x_2, z on the lower surface of the packet in the usual manner, directing the coordinate axes x_α along the adjacent sides of the panel. The origin of the coordinate system shall be placed at one of the corners of the shell, the positive direction of the normal defined so that $0 \leq z \leq h$ throughout the body of the panel, where h is its total thickness. The lowest layer, with thickness h_1, is made of an aluminum alloy with the following elastic characteristics: $E_{(1)} = 7000$ MPa, $\nu_{(1)} = 0.33$, $\sigma^-_{(1)} = 530$ MPa, $\sigma^+_{(1)} = 480$ MPa, while the upper layer, with thickness $h - h_1$, consists of a thermal protective ceramic coating with the following mechanical properties:

$$E_{(2)} = 214 \cdot 10^3 \text{ MPa},\ \nu_{(2)} = 0.25,\ \sigma_{-(2)} = 1400 \text{ MPa},\ \sigma_{+(2)} = 98.5 \text{ MPa},$$

where $\sigma^+_{(i)}$, $\sigma^-_{(i)}$, i = 1, 2, are the tensile and compressive strengths of the materials of the layers.

Assuming the contact between the layers to be ideal, and the internal structure of the materials forming the layers to be defect-free, let us determine the maximum permissible value of external load parameter p*, up to which the structure is deformed elastically without formation of internal defects.

This approach was described in [1] and corresponds to analysis only of the initial stage of failure — the moment of formation of a local defect in the structure — without analyzing the process of its subsequent development. In this problem, estimation of the serviceability of a two-layer panel based on its initial failure is accepted because for shells made of such elastic-brittle materials as ceramics, the entire load-bearing capacity is typically exhausted at loads only slightly exceeding the load at which initial failure of one layer occurs. If, after initial failure of the shell, some load-bearing capacity is retained, the formation of a defect in the coating material results in loss of its heat-insulating properties, which is also a negative factor decreasing the reliability of the entire structure.

The significant difference in the properties of the materials of the layers prevents use of the standard classical and nonclassical versions of the theory of laminar shells as solution equations, since the solution of these equations cannot provide sufficient accuracy in the determination of all stress tensor components. Since direct utilization of the equations of the three-dimensional theory of elasticity, due to its significant computational difficulties, is not possible, we utilized an iterative version of the refined theory of smooth shells [2] to determine the stress tensor components, allowing us to determine the internal stress state of the layers with greater accuracy. The procedure for computing the stress fields in this case is reduced to solving a sequence of similar boundary-value problems for a system of twelfth order differential equations in partial derivatives. For the results presented below the solution of this system was constructed using expansion of the desired functions into series with respect to derivatives of the beam functions, the specific form of which was selected according to the boundary-value conditions of the problem.

After the stress field was determined in each of the layers, the initial failure load could be computed using the results of [1] from the Balandin strength criterion [30]

$$\sum_{n=1}^{3} (\sigma_n^{(i)})^2 - (\sigma_1^{(i)}\sigma_2^{(i)} + \sigma_1^{(i)}\sigma_3^{(i)} + \sigma_2^{(i)}\sigma_3^{(i)}) + (\sigma^-_{(i)} - \sigma^+_{(i)}) \sum_{n=1}^{3} \sigma_n^{(i)} = \sigma^+_{(i)}\sigma^-_{(i)}$$

allowing us to consider the difference in tensile and compressive strengths of the materials of each layer.

Figure 1 and Figure 2 show the variation in initial failure pressure with one of the curvatures of the panel.

The geometric characteristics of the panel were taken as follows:

$$h/L = 0.05,\ h_1/h = 0.9,\ L/R_1 = 0.1,$$

where L is the length of one side of the shell in the plan, while R_1 is the radius of curvature.

The results presented in Figures 1 and 2 were obtained by bending the panel with internal pressure $P > 0$ and external pressure $P < 0$.

Calculations were performed for the following versions of support of the edges:

1. All four edges of the packet rigidly clamped;
2. Edges $x_1 = 0$ and $x_1 = L$ rigidly clamped, the other pair of edges freely supported;

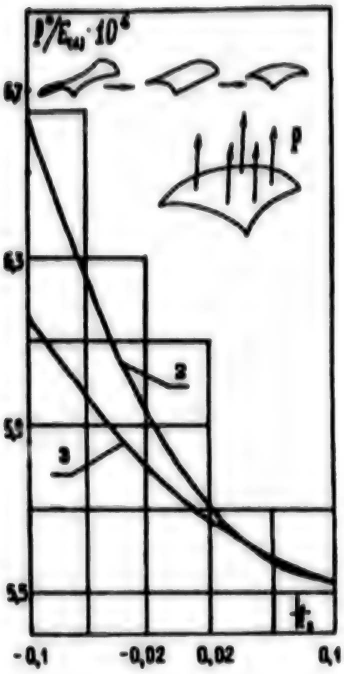

Figure 1

3. The pair of edges $x_1 = 0$ and $x_1 = L$ freely supported, edges $x_2 = 0$ and $x_2 = L$ rigidly clamped.

The numbering of the curves in the figures correspond to the type of support of the packet edges.

When the shell was bent by internal pressure, failure of the shell resulted from the tensile stresses, and started with failure of the coating material at the central point of the upper layer, where these stresses reach their maximum. The greatest load is supported by shells of negative Gaussian curvature, with edges $x_1 = 0$ and $x_1 = L$ rigidly clamped. As dimensionless parameter L/R_2 increases, the failure loads of the structure decrease.

When the panel is bent by external pressure, the ceramic layer operates primarily in compression, with the exception of narrow areas adjacent to the clamped edges, not allowing full utilization of the high compressive strength of the material. Here, as in the first case, the failure of the ceramic layer results from tensile stresses, but generation of a defect in the layer does not occur at the center of the shell, but rather at the midpoint of the clamped edges on the outer surface of the packet.

The behavior of p* with a change in parameter L/R_2 also differs from that shown in Figure 1. In this case, the maximum load-bearing capacity is that of spherical panels, the edges of which are all rigidly clamped. With the third version of support the strength of the panel is virtually independent of its geometric shape. Least strong are panels with edges supported by the second method.

We note also that with both forms of loading of the packet, the base material acts elastically, the stresses in it are significantly less than the stresses in the coating.

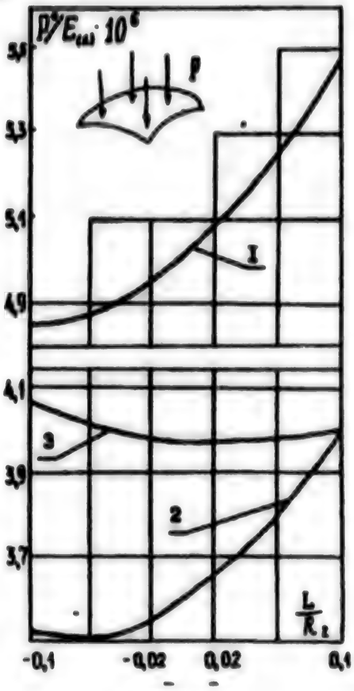

Figure 2

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UDC 39.3

NONLINEAR DEFORMATION AND STABILITY OF SHELLS OF COMPOSITE MATERIALS

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Shell structures made of high-strength composites, including metallic and metal-ceramic composites, are widely used in engineering. Their laminar structure and anisotropy of physical and mechanical properties require the use of new, more accurate approaches for calculation of the strength and stability of such elastic systems [1] and the development of universal algorithms on the basis of these approaches.

This article suggests finite-element methods of solving three-dimensional problems in the geometrically nonlinear statics of axisymmetrical shells and noncircular cylinders, as well as analysis of the stability of shell structures exposed to heat and force considering the general form of anisotropy for each layer.

By applying the method of finite elements in the form of the method of displacements, we reduce the problem of thermoelasticity to solution of a system of nonlinear algebraic equations

$$f(U) = [K_L + K_\varepsilon - K_T]U + k_N(U) - Q(\varepsilon_0, U_0, T, P_S, P_V) = 0 \quad (1)$$

by the method of Newton based on the recurrent equation

$$\begin{gathered} [K_L + \mu_n(K_\varepsilon - K_T + D(U^{(n)}))]\, U^{(n+1)} = Q - k_N(U^{(n)}) + D(U^{(n)})\, U^{(n)} \\ U^{(0)} = 0;\ \mu_0 = 0;\ \mu_i = 1;\ i = 1, 2, \ldots;\ [D_{ij}(U)] = [\partial k_{Ni}(U)/\partial U_j] \\ n = 0, 1, \ldots, N:\ \| U^{(n)} - U^{(n-1)} \| < \delta \end{gathered} \quad (2)$$

Here, Q is the vector of applied forces, k_L is the linear rigidity matrix; the matrices $K\varepsilon(\varepsilon_0)$, KT(T) and the vector kN(U) result from the geometric nonlinearity.

By introducing the load parameters λ_ε, λ_U, λT, λS and λV and, following [2], studying the full variation of (1), we obtain that the solubility of (1) follows from the solubility of

$$\begin{gathered} [K_L + K_\varepsilon - K_T + D(U)]\delta U = [\cdot\frac{\partial Q}{\partial \lambda_\varepsilon} - \frac{\partial K_\varepsilon}{\partial \lambda_\varepsilon} U]\delta\lambda_\varepsilon + \\ + [\frac{\partial Q}{\partial \lambda_T} + \frac{\partial K_T}{\partial \lambda_T} U]\delta\lambda_T + \frac{\partial Q}{\partial \lambda_U}\delta\lambda_U + \frac{\partial Q}{\partial \lambda_S}\delta\lambda_S + \frac{\partial Q}{\partial \lambda_V}\delta\lambda_V \end{gathered} \quad (3)$$

for the increment δU. A necessary and sufficient condition for existence and uniqueness of the finite-element solution of the nonlinear problem of thermoelasticity with load level $\bar{\lambda}_\varepsilon, \ldots, \bar{\lambda}_V$ is positiveness of the Jacobian matrix $[J_{ij}] = [\partial f_i/\partial U_j]$ *of system (1) in the multivariate area of loading:* $(0 \le \lambda_\varepsilon \le \bar{\lambda}\varepsilon, \ldots, 0 \le \lambda V \le \bar{\lambda}$ $\det J(U) \ge 0$. Equations (2) and (3) indicate the possibility of studying both the stress state and stability on the basis of a single algorithm, using a combination of the methods of Newton and successive loadings. With monotonic variation of the solution vector as a function of the load parameter, it is possible to study the supercritical behavior without the use of methods of parameters continuation.

Linear and geometrically nonlinear initial states were studied to solve the linearized problem of stability. In the former case, as a result of application of the discrete analogue of the energy criterion of stability and representation of the solution for the deflected state in Fourier series, the problem is reduced to an algebraic problem of eigenvalues: $[\overset{*}{K} + \lambda \overset{*}{G}(\overset{o}{U})]\overset{*}{U} = 0$. In the latter case, the sequence of problems of finding the null of the determinant $\det[\overset{*}{K}L + \overset{*}{G}(\overset{o}{U}m)]$ is solved (here (^{o}) represents membership in the initial state, (*) represents membership in the deflected state; $\overset{*}{G}$ is the geometric rigidity matrix, $\overset{o}{G}m$ is the solution of problem (1) at load level m).

Based on analysis of the variability of the solution and the anisotropy of mechanical properties of the materials of shell structures, recommendations have been developed for the construction of rational grids of finite elements, resistant to comutational errors.

Figure 1 shows the variation of meridional force with temperature of uniform heating, considering the supercritical area of a two-layer, transversely reinforced ($\gamma = \pm 30°$) cylindrical shell rigidly fixed at its ends (H - 4 mm; R = 1000 mm; L = 200 mm; $E_a/E_m = 36.3$; $\nu_a = 0.2$; $\nu m = 0.39$; $\alpha a = 3.8 \cdot 10\text{-}6\ °C^{-1}$; $\alpha_a = 6.0 \cdot 10^{-5}\ ° X^{-1}$). The critical temperature $\tau_* = 90$ °C is defined. Figure 2 shows the distribution of stresses through the thickness of the shell near an edge ($\alpha_2 = 2$ mm) at the critical temperature. The

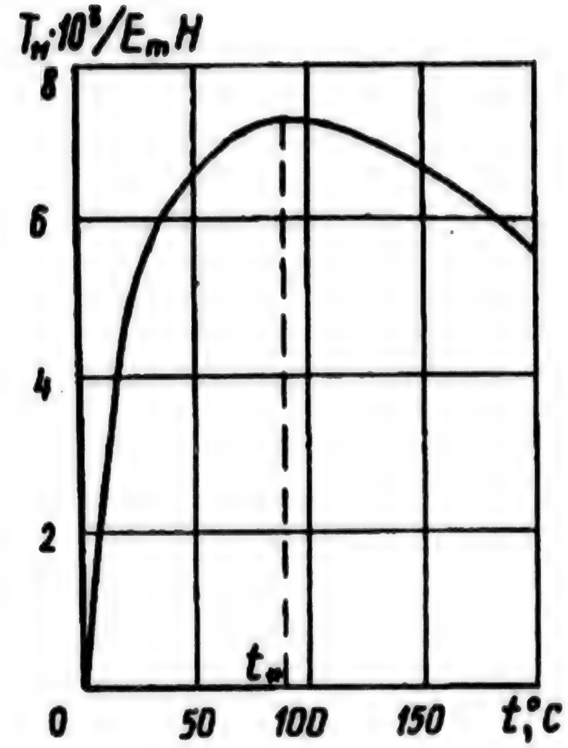

Figure 1

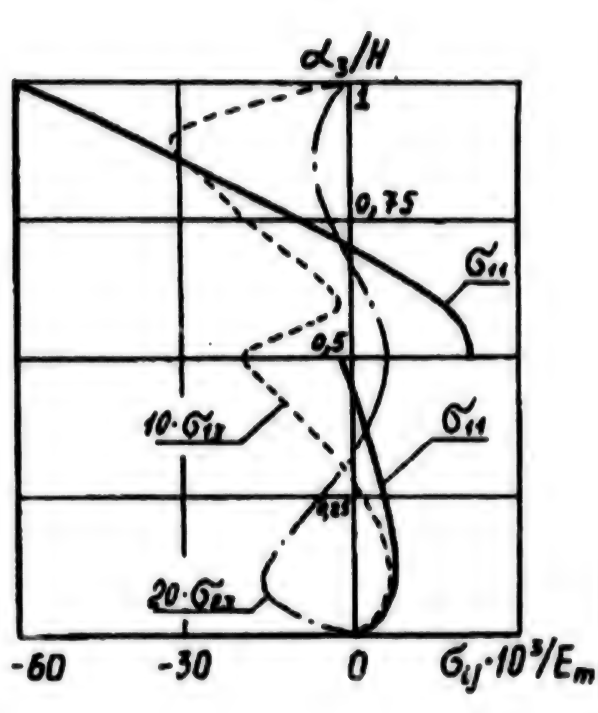

Figure 2

complex distribution of transverse shear stress is characteristic.

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UDC 539.3:519

NUMERICAL MODELING OF STRESS-STRAIN STATE OF PRODUCTS OF METAL COMPOSITES WEAKENED BY APERTURES

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In recent years, work on increasing the strength and durability of machine parts by the use of intentional mechanical heterogeneity of the parts has developed rapidly. In some cases, the necessary heterogeneity can be created in a part made of an initially homogeneous material by setting up a system of residual stresses and by mechanical hardening [1], while in other cases the required heterogeneity is created by the use of composite materials [2].

Among the entire variety of machine parts in which heterogeneous materials are useful, a particular place is occupied by the class of parts consisting of plates with apertures (such as the load-bearing panels of an aircraft wing, et cetera). One of the main factors which must be considered in the design stage of such parts is the concentration of stresses around apertures or other structural stress concentrators.

In connection with the extensive use of materials with intentional heterogeneity (composites, materials with coatings) in the creation of machine-structure products with concentrators, calculation methods considering the characteristic heterogeneity and sudden changes in properties of these materials are quite important.

This article outlines the principles of a numerical method of computing the stress-strain state of composite products, based on the use of graphic models of heterogeneous media and presents the results of analysis of the stress-strain state of plate-type composite products with apertures, having various versions of reinforcement of these apertures, and their computation based on strength criteria.

The numerical method we have developed for computing the stress-strain state of heterogeneous bodies is based on the use of a discrete model of a body consisting of an oriented graph [3]. The topologic rules of graphs, expressed as simple algebraic equations, are equivalent to systems of differential equations of equilibrium and compatibility of deformation from the theory of elasticity. These rules include an incidence matrix, which is used in the formation of equations of state of a body based on the equations of state of its individual parts. The method allows the elements into which the area studied is divided to be placed arbitrarily close, and has reduced requirements to the relationship of dimensions of the elements. This allows, in particular, computation of the stress state of very thin interlayers (e.g., in adhesive joints). Another advantage of the graphic method is the possibility of solving problems with large numbers of dimensions (several thousand or more equations) while decreasing the computational error. An application software package has been developed to implement the method, distinguished by its simplicity and designed for implementation in the environment of the OS YeS operating system on a YeS-1022 or larger computer. The software package implements an effective yet rather simple procedure for automated subdivision of a body into elements. [Footnote: The software package is now being modified to run on IBM PC-AT-compatible personal computers.]

The software package was used to solve a number of problems of stress-strain state analysis and design of a number of composite-material products based on strength criteria, including specifically rectangular orthotropic plates of finite dimensions 2a and 2b, weakened by a central rectangular aperture or a circular aperture of radius R. In the latter case, versions with reinforcement of the plates were also studied: 1) by a rigid ring with inner and outer radii R_1 and R; 2) by an inclusion of arbitrary shape. It was assumed that the plates are in uniaxial extension and that, depending on the support version, the inner contour of the ring or the contour of the aperture in the plate was free of external loading. The material of the ring and the inclusion has greater elastic characteristics than the plate. The load-bearing capacity of such a structure is determined by the strength characteristics of the ring (or inclusion) in the plate, as well as the strength of the contact surface, since the reason for failure may be either failure of the structural elements or of the bond which joins them. In designing plates one must consider which of the structural elements under specific loading conditions will

fail first. Therefore, the solution of the problem of predicting the load-bearing capacity is based on analysis of the stress-strain state of the entire structure considering the strength characteristics of its components. This problem was solved both with rigid bonding of the ring (or inclusion) to the plate, and considering the strength of the actual bond. The strength criterion of the components of the composite product was accepted as [4]

$$\varkappa\sigma_i + (1-\varkappa)\sigma_1 = \sigma_{\varkappa 0} \leq \sigma_0^+ ,$$

where

$$\varkappa = \sigma_0^+/\sigma_0^- ; \quad \sigma_i = [(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2]^{0.5}/\sqrt{2}$$

(here σ_0^+, σ_0^- are the tensile and compressive strengths of the material; σ_i is the load intensity; $\sigma 1$, σ_2 and σ_3 are the major stresses).

The strengths of the materials of the ring (or inclusion) and the plate, as well as the bond strength of the ring with the plate, both tensile and shear, dependent on the characteristics of the contacting materials and the technology used to make the joint, were determined experimentally.

In the process of the calculations we computed: 1) the components of stress and the major stresses in each element into which the entire area was divided; 2) the stress levels of each element (ratio of equivalent stress to tensile strength of the material of the element, i.e., stress level — the reciprocal of the strength reserve factor); 3) the stress levels of the materials of the ring (or inclusion) and plate, as the maximum stress level of all elements of the material in question; 4) the stress levels of elementary boundaries dividing the materials, as the ratio of equivalent stress to tensile stress of the interface; 5) the stress levels of the boundaries between materials, as the maximum stress level of all elements on the boundary between the materials; 6) the stress level of the entire structure (maximum stress level of materials and boundaries between materials).

During the numerical calculations, the geometric, elastic and strength characteristics of the plate and ring (inclusion) were varied, as were the tensile and shear strength of the joints between the materials. As a result of the calculations, the permissible loads on the structure and its strength reserve were determined and the process of failure was elucidated. In particular, for the case in which an aperture in a duralumin plate was reinforced by a steel ring, analysis of the results of the calculation leads to the following conclusions:

1. Failure of a structure almost always begins with failure of the joint between the ring and the plate;

2. In the rather complex behavior of the stress level along the line of separation of the materials there are two characteristic maxima. They are found at points located at angles of 75-80° and 45° to the direction in which the load is applied;

3. As the load increases, the maximum of the stress level of the interface grows most rapidly at a point oriented at an angle of 45° ;

4. The shear strength of the joint has a great influence on the stress on the interface. As it increases, the stress on the interface significantly decreases;

5. As the thickness of the supporting ring decreases to less than 1 mm, points with the maximum interface stress may shift from a line oriented at 45° to the application of the load in the direction of the transverse axis through the plate;

6. For real values of elastic and strength characteristics of the materials of the plate, ring and their bond strength, the load-bearing capacity of a reinforced plate is 1.5 times greater than the load-bearing capacity of a plate without reinforcement.

Comparison of the calculated results obtained with the results of experimental studies on plates of aluminum alloys with apertures supported by high-strength steel rings by pulsed loadings has demonstrated the good agreement of calculated and experimental results.

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UDC 539.3

NUMERICAL-ANALYTIC SOLUTION OF NONLINEAR DYNAMIC PROBLEMS OF THINWALL COMPOSITE STRUCTURAL ELEMENTS

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In connection with the extensive application and use in engineering practice of new composite materials and elements of structures made of them, the question of constructing a theory of plates and shells considering the characteristic features of these materials becomes ever more pressing. Recently, this problem has been given significant attention. A number of approaches have been made to the construction of an applied theory considering the rheological properties of composite materials. Among them the most general is the model of the hereditary figure of viscoelasticity for an anisotropic body. However, the solution of nonlinear dynamic problems of the hereditary theory of viscoelasticity for an anisotropic body involves significant mathematical difficulties, since the initial equation system is a complex system of nonlinear integro-differential equations in partial derivatives. Such problems are linearized in order to avoid the mathematical difficulties related to the solution of nonlinear integro-differential equations. In order to overcome these difficulties, a number of works have introduced extremely limiting conditions for the nonlinear portions of the equations and the integral terms. These limitations mean that certain important cases in which the nonlinear portions of the equations and integral terms considering the hereditary properties of the materials significantly influence the solution of the problem are not included. Serious difficulties are encountered in the process of digitization of spatial variables in nonlinear dynamic viscoelasticity problems.

Therefore, the development of new and the refinement and improvement of existing methods of solving initial-boundary-value problems of hereditary solid-state mechanics are of both theoretical and practical interest.

This article suggests effective approaches to numerical-analytic solution of certain dynamic problems related to elements of thinwall structures in the form of viscoelastic plates and shells with arbitrary external influences. The algorithm for solution of the problem consists of several stages of decreasing its dimensions. In the first stage a continual system is reduced by means of the Bubnov-Galerkin method (method of finite elements) to an adequate discrete problem, then the method of expansion with respect to forms of natural oscillations of elastic systems reduces the problem to integration of nonconnected, nonlinear, ordinary integro-differential equations, the precise solutions of which can be found in the linear case by methods outlined in [1, 2]. In the nonlinear case an approach is used which is based on a rational combination of analytic transforms and a stable numerical method of integration of the integro-differential equations as in [1].

Suppose as a result of discretization of the initial continual problem we obtain the following system of ordinary nonlinear integro-differential equations

$$M\ddot{u} + A\left[u - \int R(t-\tau)u(\tau)d\tau\right] = f(t) + G\left(u, \int \Gamma(t-\tau)u(\tau)d\tau\right), \quad (1)$$

where M and A represent the matrix of masses and linear rigidity; u is the vector of unknown nodal displacement; G[,] is the vector of the nonlinear portion of the equilibrium equations; $f(t)$ is the load vector; R(t), Γ(t) are the linear and nonlinear kernels of the relaxation, having weak Abelian singularities.

It is generally impossible to construct an analytic solution of (1) even in the linear case, while direct numerical integration is practically impossible due to the high order of the system of integro-differential equations. Therefore, the problem is solved by expansion with respect to forms of natural oscillations of elastic systems, considering that in the linear case with this approach the problem is reduced to integration of nonconnected integro-differential equations, allowing the construction of a precise analytic solution [2], while in the nonlinear case there is a stable computing algorithm to produce the numerical solution with the required degree of accuracy [1]. We shall seek the solution as

$$u(t) = \sum_{i=1}^{n} y_i(t)\bar{W}_i \quad (2)$$

where $y_i(t)$ is the ith generalized coordinate;

$\bar{W}_c$ is the form of the natural oscillations of an

elastic system corresponding to the ith natural frequency θi. Using the approach of [2], we obtain the equation of motion in normal coordinates:

$$\ddot{y}_i + \omega_i^2 [y_i - \int R(t-\tau) y_i(\tau) d\tau = q_i(t) + G_i(y_1, \dots, y_n, \int \Gamma(t-\tau) [y_1(\tau), \dots, y_n(\tau)] d\tau, \quad (3)$$

where

$$q_i(t) = (f(t), \bar{W}_i), \quad G_i = (G, \bar{W}_i).$$

The solution of each of these equations with the initial conditions $y_i(0) = y_i(0)$, $\dot{y}_i(0) = y^{(1)}_i$ is an easier task than the solution of the initial system (1). In the linear case according to [1, 2] the precise solution of system (3) is

$$y_i(t) = y_i^{(0)} V_{ci}(t) + \frac{y_i^{(1)}}{\omega_i} V_{si}(t) + \frac{1}{\omega_i} \int V_{si}(t-\tau) q_i(\tau) d\tau, \quad (4)$$

where

$$V_{ci}(t) = \cos \omega_i t + C\varphi(\omega_i t), \quad V_{si}(t) = \sin \omega_i t + S\varphi(\omega_i t)$$

$c\phi(\omega_i t)$, $\sigma\phi(\omega_i t$ are the cosine and sine of the fractional order [2].

The precise solution of (9) leads us to a number of new mechanical effects which cannot be established by numerical or approximate analytic methods [1, 2]. In particular, it is established that the oscillations of viscoelastic systems under the influence of a constant external load occur about the curve of the creep function and attenuate along the same curve as time passes.

In the nonlinear case a numerical method is suggested, based on the use of quadrature equations. At first, system (3) is written in integral form, then, assuming $t = t_m$; $t_i = jh$; $j = \overline{1,m}$; $m = 1, 2, \dots$ ($h =$ const) replacing the integrals with certain quadrature equations, we obtain the following approximate equation for computation of $y_{im} = y_i(t_m)$

$$y_{im} = y_i^{(0)} V_{ci}(t_m) + \frac{y_i^{(1)}}{\omega_i} V_{si}(t_m) + \frac{1}{\omega_i} \sum_{j=0}^{m} A_j [q_i(t_j) + G_i[y_1(t_j), \dots, y_n(t_j), \sum_{k=0}^{j} B_k \Gamma_{j-k} (y_1(t_k), \dots, y_n(t_k))]] V_{si}(t_m - t_j),$$

where

$$A_j, \ B_k, \ j = \overline{0,m}, \ k = \overline{0,j}, \ m = 1, 2, \dots$$

are numerical coefficients independent of the selection of the integrand functions, taking on various values depending on the quadrature equations used. The error in this method coincides with the error obtained in the use of quadrature equations and has the same order of magnitude with respect to interpolation step.

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UDC 539.3

COMPUTATION OF DEFORMATION OF VISCOELASTIC RODS OF COMPOSITE MATERIALS UNDER DYNAMIC COMPRESSIVE LOADS

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We know [1, 2] that many dynamic problems related to the oscillation of rods and beams made of composite materials with viscoelastic properties are reduced in their physically and geometrically nonlinear statements to solution of nonlinear integro-differential equations with variable coefficients such as:

$$\ddot{T}_n + \omega_n^2 [1-\mu_n p(t)] T_n = x_n \Big\{ t, T_1, \ldots, \int_0^t \varphi_n(t, \tau, T_1(\tau), \ldots, T_N(\tau))\, d\tau \Big\}, \qquad (1)$$
$$T_n(0) = T_{0n}, \quad \dot{T}_n(0) = \dot{T}_{0n}, \quad n = 1, 2, \ldots$$

where $T_n = T_n(t)$ are the desired functions of time; p, x_n and φ_n are assigned continuous functions in the area within which the arguments change;

In [3] a numerical method was suggested for systems of integro-differential equations, based on the use of quadrature equations. According to [3], the numerical values of the desired function $T_{in} = T_n(t_i)$ can be found from the equations

$$T_{in} = T_{0n}\cos\omega_n t_i + \frac{\dot{T}_{0n}}{\omega_n}\sin\omega_n t_i + \frac{1}{\omega_n}\sum_{j=0}^{i-1} A_j^{(n)} \Big\{ \mu_n \omega_n^2 p(t_j) T_{jn} + x_n\Big(t_j, T_{j1}, \ldots, T_{jN}, \sum_{k=0}^{j} B_k^{(n)} \varphi_n(t_j, t_k, T_{k1}, \ldots, T_{kN})\Big)\Big\} \times \sin\omega_n(t_i - t_j), \quad i = 1, 2, \ldots, \quad n = 1, 2, \ldots, N, \qquad (2)$$

where $A^{(n)}_j$, $B^{(n)}_k$ are numerical coefficients independent of the selection of integrand functions, taking on various values depending on the quadrature equations used.

Let us study the problem of oscillations of a viscoelastic rod articulated at the ends and subject to the influence of compressive force p(t), changing with time t. We assume that the rod has the initial bend $U_0 = U_0(x)$ and that its cross section is constant over its length. The differential equation of the bent axis of the viscoelastic rod under these assumptions after introducing the dimensionless quantities similar to [2], becomes

$$(1-R^*)\frac{\partial^4(u-u_0)}{\partial x^4} + p(t)\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial t^2} = \gamma(1-R^*)\Big[2\frac{\partial^2(u-u_0)}{\partial x^2} \times \Big(\frac{\partial^3(u-u_0)}{\partial x^3}\Big)^2 + \Big(\frac{\partial^2(u-u_0)}{\partial x^2}\Big)^2 \frac{\partial^4(u-u_0)}{\partial x^4}\Big] + f(x,t), \qquad (3)$$

where γ is an assigned dimensionless parameter.

The solution of equation (3) satisfying the boundary-value conditions of the problem, will be sought as

$$u(x,t) = \sum_{n=1}^{N} T_n(t)\sin\frac{n\pi x}{\lambda}, \quad u_0(x) = \sum_{n=1}^{N} T_{0n}\sin\frac{n\pi x}{\lambda} \qquad (4)$$

Substituting (4) and (3), and performing the Bubnov-Galerkin procedure to determine $T_k(t)$ we obtain the following system of nonlinear integro-differential equations:

$$\ddot{T}_n + \omega_n^2\Big\{\Big[1-R^* - \frac{p(t)}{\omega_n}\Big]T_n - (1-R^*)T_{0n}\Big\} = f_n(t) - \gamma(1-R^*)\sum_{n=1}^{N}\sum_{i=1}^{N}\sum_{j=1}^{N} a_{nijn}(T_n - T_{0n})(T_i - T_{0i})(T_j - T_{0j}), \qquad (5)$$
$$T_n(0) = T_{0n}, \quad \dot{T}_n(0) = \dot{T}_{0n}, \quad n = 1, 2, \ldots, N,$$

here the coefficients included in system (5) are determined by the equations

$$\omega_n^2 = (n\pi/\lambda)^4, \quad a_{nijn} = \frac{1}{4}\omega_n\omega_i\omega_j\{2\sqrt{\omega_i\omega_j}(\delta_{n+n+i+j} + \delta_{n+n+i-j} + \delta_{n+n-i+j} - \delta_{n-n+i+j} - \delta_{n-n+i-j} - \delta_{n-n-i+j} - \delta_{n+n-i-j}) + \omega_j(\delta_{n+n-i-j} - \delta_{n-n+i+j} - \delta_{n+n-i+j} - \delta_{n-n+i-j} - \delta_{n-n+i+j} + \delta_{n-n-i-j} + \delta_{n+n+i+j})\}, \quad \delta_k = \begin{cases} 1, & k = 0, \\ 0, & k \neq 0. \end{cases}$$

We note that system (5) is a particular case of system (1). We will seek it by a numerical method suggested in [3]. The numerical values of $t_{in} = T_n(t_i)$ are determined from equation (2). Computation of the values of T_{in} using equation (2) was performed on a YeS-1061 computer. THe following initial data were used:

$$p(t) = V_0 t, \quad V_0 = 1{,}28; \quad f_n(t) = f_0 = t; \quad \lambda = 10, \quad N = 5,$$
$$R(t) = At^{\alpha-1}\exp(-\beta t), \quad A = 0{,}05; \quad \alpha = 0{,}25; \quad \beta = 0{,}05; \quad \gamma = 0{,}5;$$
$$T_n(0) = 0{,}8\cdot(-1)^m\exp(-3)/n^4, \quad \dot{T}_n(0) = 0,$$

where $m = n/2$ where n is even and $m = (n+1)/2$ where it is odd.

Figure 1 shows the form of the oscillations of the midpoint of an elastic rod (curve 1), a viscoelastic rod in the linear case (curve 2), a viscoelastic rod with no initial bend (curve 3) and a viscoelastic rod in the nonlinear case with an initial bend (curve 4).

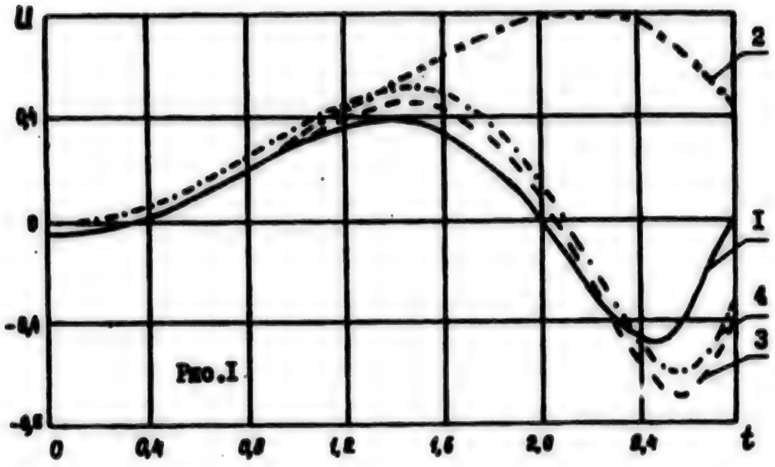

Figure 1

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UDC 539.3:519

BOTTOM SHAPE OF PRESSURE CYLINDERS MADE OF UNIDIRECTIONAL COMPOSITE MATERIALS WITH LOW SHEAR RIGIDITY

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A typical computation model of a reinforced pressure cylinder is the "grid method" in which the load-bearing capacity of the binder is ignored. The use of an orthotropic model for a unidirectional material is desirable for such high-modulus materials as carbon-boroplastics, in which failure of the reinforcing elements is preceded by failure of the binder. This article studies an intermediate model. We can write the basic equations (1) for an envelope of rotation (Figure 1) consisting of a symmetrical spiral winding with angles ±φ and loaded by uniform internal pressure *q*.

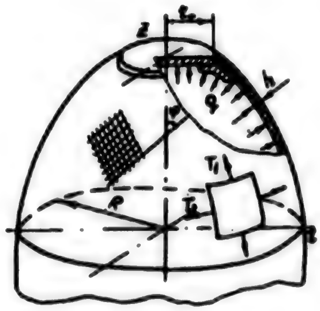

Figure 1

The equilibrium equations are:

$$\begin{cases} \frac{d(rT_1)}{dr} - T_2 = 0 \\ \frac{T_1}{R_1} + \frac{T_2}{R_2} = q \end{cases} \qquad (1)$$

The static equations are:

$$\frac{T_1}{h} = \sigma_1\cos^2\varphi + \sigma_2\sin^2\varphi - \tau\sin 2\varphi$$
$$\frac{T_2}{h} = \sigma_1\sin^2\varphi + \sigma_2\cos^2\varphi + \tau\sin 2\varphi \qquad (2)$$

Hooke's law is:

$$\sigma_1 = \frac{E_1}{1-\mu_1\mu_2}(\varepsilon_1 + \mu_2\varepsilon_2);$$
$$\sigma_2 = \frac{E_2}{1-\mu_1\mu_2}(\varepsilon_2 + \mu_1\varepsilon_1); \qquad (3)$$
$$\tau = G\gamma_{12}$$

The condition of deformation compatibility is:

$$\varepsilon_1 - \varepsilon_2 + \gamma_{12}\,\mathrm{ctg}\,2\varphi = 0. \qquad (4)$$

Substituting (2) into the first equation of system (1) and considering the condition of continuity of the winding $2\pi rh\cos\varphi = \text{const}$, we obtain

$$+\sigma_2\left[\frac{(2+\mathrm{tg}^2\varphi)\,\mathrm{tg}\,\varphi}{\xi}\frac{d\xi}{dr} - \frac{1}{r\cos^2\varphi}\right] - \frac{E_1}{r}\frac{d\xi}{dr} = 0 \qquad (5)$$

where $\xi = r\sin\varphi$ is the Clairaut function. From equations (2-4) we find

$$\frac{T_2}{T_1} = \frac{\sin^2\varphi\cos 2\varphi - \frac{E}{\bar E_1}\sin^2 2\varphi + K(\cos^2\varphi\cos 2\varphi + \frac{E}{\bar E_2}\sin^2 2\varphi)}{\cos^2\varphi\cos 2\varphi + \frac{E}{\bar E_1}\sin^2 2\varphi + K(\sin^2\varphi\cos 2\varphi - \frac{E}{\bar E_2}\sin^2 2\varphi)} \qquad (6)$$

where

$$K = \frac{\bar E_2}{\bar E_1}; \quad \bar E_1 = \frac{E_1}{1-\mu_1\mu_2}; \quad \bar E_2 = \frac{E_2}{1-\mu_1\mu_2}.$$

On the other hand for a shell which is closed at the pole by a cover we find from (1) that

$$\frac{T_2}{T_1} = 2 - \frac{R_2}{R_1} \qquad (7)$$

where R_2, R_1 are the main radii of curvature of the shell.

Equations (5-7) allow us to study a number of design problems by arbitrary assigning the rule for change of two parameters (geometric or strength). Thus, in [1], equal-strength bases of high-modulus composites were studied, reinforced on the trajectories of the main stresses for which $\tau = \gamma_{12} = 0$ while the stresses along the tape σ_1 and across the tape σ_2 are constant. Here $K = E_2/E_1 = \text{const}$. The trajectories of reinforcement providing this distribution of stresses are nongeodetic and are described by the equation

$$r\cos^2\varphi[1-(1-K)\cos^2\varphi]^{\frac{1-K}{2}} = \text{const}$$

Let us study a unidirectional material, with rigidity along and across the reinforcement but with little resistance to shear ($G \to 0$). This model corresponds, for example, to deformation of a two-matrix composite, analyzed in [2], and occupies an intermediate

position between the network and orthotropic. In this case the problem becomes statically defined.

Let us find the form of an equal-strength shell of this material. Assuming

$$\sigma_1 = \sigma_1^0 = const, \xi = const, \tau = 0, (\gamma_{12} \neq 0)$$

we find from (5)

$$\frac{\sin^2\psi}{\cos\psi}\frac{d\sigma_2}{dr} - \frac{\sigma_2}{r\cos^3\psi} = 0. \quad (8)$$

The solution of this last equation is

$$\sigma_2 = \sigma_2^0\left(\frac{r^2 - r_0^2}{R^2 - r_0^2}\right)^{k_0} e^{\frac{r^2 - R^2}{2r^2}} \quad (9)$$

According to (9), the stresses σ_2 decreases rapidly from the value of σ_0^2 at the equator of the base *(r = R)* to zero at the pole.

Representing ψ as the angle between a perpendicular to the shell and the axis or rotation and assuming in (6) G = 0, based on equation (7) we can find the profile of the base.

$$\begin{cases} \frac{d\sin\psi}{dr} = \frac{\sin\psi}{r}\left[2 - \frac{r^2 - (1-K)(r^2 - r_0^2)}{Kr^2 + (1-K)(r^2 - r_0^2)}\right] \\ \frac{dz}{dr} = \operatorname{tg}\psi \end{cases} \quad (10)$$

where

$$K = \frac{\sigma_2^0}{\sigma_1^0}\left(\frac{r^2 - r_0^2}{R^2 - r_0^2}\right)^{k_0} e^{\frac{r^2 - R^2}{2r_0^2}}$$

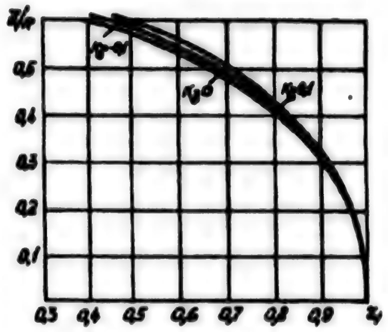

Figure 2

Figure 2 shows profiles of the base calculated by computer using equations (10) for r0/R = 0.3. The boundary conditions of the Cauchy problem are: r = R, z = 0, $\psi = \pi/2$. The graphs were calculated for $k_0 = \sigma^{02}/\sigma_{01}$ = -0.1, 0, 0.1, 0, 0.1. The version with k_0 = 0 corresponds to the method of grids.

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UDC 539.3

CALCULATION OF STRESS STATE OF REINFORCED FLEXIBLE SPHERICAL SHELLS

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The complex usage conditions of products exposed to various loading factors require ever more extensive utilization of composite materials. One practically important problem is that of the stress state of spherical shell elements made with reinforcing fibers, the major directions of elasticity in which do not coincide with the directions of the coordinate lines.

We study here axisymmetrical deformation of flexible reinforced orthotropic spherical shells, by consideration of the transverse shear deformation using a Timoshenko-like model. The geometry of the shell is related to a curved orthogonal system of coordinates S, Θ, Z, where S is the length of an arc of the meridian, Θ is the central angle in the parallel arc, Z is read in the direction of an external normal to the selected coordinate surface. A study is made of the geometrically nonlinear theory of shells in its quadratic approximation. Consideration of the difference between the main directions of elasticity and the directions of the coordinate lines requires complication of the initial equations [1].

This problem is described by a boundary-value problem for a system of ordinary differential equations such as [2]

$$d\bar{N}/ds = F(s, \bar{N})$$

with boundary conditions which in the case of assignment of a certain linear combination of desired functions are represented as follows:

$$B_0\bar{N}(s_0) = \bar{b}_0, \quad B_N\bar{N}(s_N) = \bar{b}_N, \quad s_0 \le s \le s_N,$$

where B_0, B_N are rectangular matrices, $\bar{B}_0$, $\bar{B}_N$ are assigned vectors, $\bar{N} = \{U, W, \Psi_1, N_1, Q^*_1, M_1\}$, U is the meridional displacement, W is the flexure, Ψ_1 is the full angle of inclination of the normal to the coordinate surface in the planes Θ = const, N_1, Q^*_1 are the meridional and shear forces, M_1 is the bending moment.

The solution of the nonlinear boundary-value problems as a result of application of the method of quasilinearization leads to a sequence of solutions of the linear boundary-value problems which can be represented as

$$\frac{d\bar{N}^{n+1}}{ds} = \bar{F}(s, \bar{N}^{n+1}, \bar{N}^{n}),$$
$$B_0\bar{N}^{n+1}(s_0) = \bar{b}_0, \quad B_N\bar{N}^{n+1}(s_N) = \bar{b}_N,$$
$$n = 0, 1, 2, \ldots$$

The solution of each linear boundary-value problem is obtained by a stable numerical method allowing results to be obtained with a practical degree of accuracy. This approach was implemented in a computer program for the YeS computers [3].

The stress-strain state of an articulated hemisphere with an aperture at the pole was computed for the case when the contour of the hemisphere was not stressed. The shell was made of an orthotropic material, the major directions of elasticity of which were rotated relative to the coordinate axes S and Θ by the angle φ, and was exposed to uniform internal pressure $q_n = q_0$. The calculations were performed for the following values of the parameters: $E_1 = 2\cdot10^5$; $E_2 = 3\cdot10^5$; $\nu_{12} = 0.1$; $G12 = 2\cdot104$; $G_{13} = G_{23} = 1\cdot10^4$; here E_1, E_2 are the elasticity moduli in direction S and Θ; ν_{12} is Poisson's ratio; G12, G_{13} and G_{23} are the shear moduli; $\varphi = 0, \pi/12, \pi/6, \pi/4, \pi/3, 5\pi/12, \pi/2$; $\Sigma_0 = 26.18$; $\Sigma_\varphi = 78.39$; $\eta/P = 1/50$.

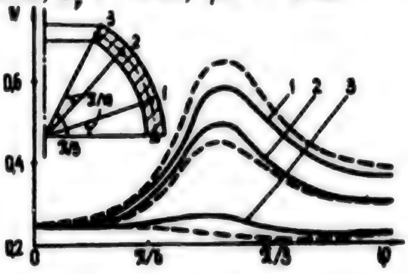

Figure 1

The results of the calculation are shown in Figures 1 and 2. The change in flexure W at three points (1-3) on the meridian of the shell as a function of winding angle is shown in Figure 1. Here the dash and solid lines correspond to solutions of the problem

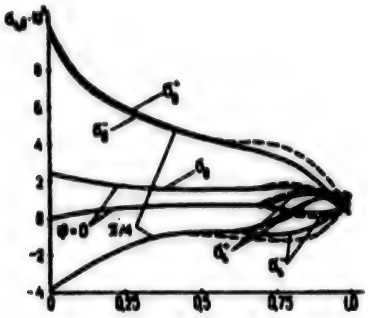

Figure 2

in the linear and geometrically nonlinear statements.

The distribution of meridional and circular stresses along the meridian of the shell for two values of winding angle $\varphi = 0$ and $\pi/4$ can be seen in Figure 2. The results presented indicate that for the material here in question with reinforcement angles $0 < \varphi < \pi/6$, $\pi/3 < \varphi < \pi/2$ the stress state of the spherical element shell can be computed in the linear statement. At reinforcement angles $\pi/6 < \varphi < \pi/3$, it is best to use the geometrically nonlinear theory to estimate the stress and strain, since it allows the solution of the problem to be obtained 15-20% more accurately.

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LIMITING STATE OF MULTILAYER COMPOSITE PLATES AND SHELLS WITH VARIABLE LOADING

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In this work, the problem of the limiting state of multilayer composite plates and shells with variable loading is solved by means of equations from the theory of limiting states (e.g., see [1]). A rigid-plate model of a deformable solid body is used. The composite structure is formed by superimposition of n orthotropic quasihomogeneous layers. In general, the layers are of different thickness and have different strength characteristics which must be determined experimentally by an assigned loading program. It is assumed that all layers reach their limiting state simultaneously.

Let us introduce the basic system of coordinates $0\xi_1$, $\xi_2\zeta$ (the ξ_1 and ξ_2 axes are coupled with the loading directions or with the lines of main curvature of the shell, the z axes is perpendicular to the surface S_0). The system $(0xyz)_j$ is coupled to the main axes of orthotropy of layer j. The orientation of layer j in the packet is determined by the angle. The orientation of layer m in the packet is determined by the

angle φ_j between the layers c_1 and x_j. The components of the stress tensor can be represented as the sum:

$$\sigma^{ik} = \sigma_m^{ik} + \sigma_a^{ik}, \quad i,k = x,y,z \vee \overline{1,3}, \tag{1}$$

where σ_{ikm}, σ_{ika} are the constant and time-variable parts of the stress (for convenience, the indices may be written as superscripts or subscripts). The procedure of deriving the basic equations is similar to that outlined in [2]. The equation of the limiting surface for layer j is most simply written in the system $(0xyz)_j$ as

$$\begin{aligned}&(\alpha\sigma_{xx}^2 + \beta\sigma_{xx}\sigma_{yy} + \gamma\sigma_{yy}^2 + \delta\sigma_{xy}^2 + \mu\sigma_{xx} + \nu\sigma_{yy} + \varphi\sigma_{xz}^2 + \psi\sigma_{yz}^2)_m^j +\\ &+ (\alpha_1\sigma_{xx}^2 + \beta_1\sigma_{xx}\sigma_{yy} + \gamma_1\sigma_{yy}^2 + \delta_1\sigma_{xy}^2 + \varphi_1\sigma_{xz}^2 + \psi_1\sigma_{yz}^2)_a^j +\\ &+ (\zeta\sigma_m^{xx}\sigma_a^{xx} + \xi\sigma_m^{xx}\sigma_a^{yy} + \tau\sigma_m^{yy}\sigma_a^{xx} + \omega\sigma_m^{yy}\sigma_a^{yy})_j = 1.\end{aligned} \tag{2}$$

The coefficients $\alpha_j, \beta_j, \ldots, \omega_j$ are experimentally determined. In the system

$0\xi_1\xi_{2z}$ equation (2) becomes

$$(\vec{\sigma}^T A \vec{\sigma} + 2\vec{B}^T\vec{\sigma} + \vec{\tau}^T C \vec{\tau} - 1)_j = 0, \tag{3}$$

where

$$\vec{\sigma} = \{\sigma_i\}, \quad A = [a_{ik}], \quad \vec{B} = \{b_i\}, \quad i,k = \overline{1,6};$$
$$\vec{\tau} = \{\tau_i\}, \quad C = [c_{ik}], \quad i,k = \overline{1,4}.$$

The components of the matrices A_j,

C_j and the vector $\vec{B}$ depend linearly on

$\alpha_j, \beta_j, \ldots \omega_j$ are functions of the angle γ_j. The following symbols are used in (3):

$$\begin{aligned}&\sigma_1 = \sigma_m^{11},\ \sigma_2 = \sigma_m^{22},\ \sigma_3 = \sigma_m^{12},\ \sigma_4 = \sigma_a^{11},\ \sigma_5 = \sigma_a^{22},\ \sigma_6 = \sigma_a^{12};\\ &\tau_1 = \sigma_m^{13},\ \ \tau_2 = \sigma_m^{23},\ \ \tau_3 = \sigma_a^{13},\ \ \tau_4 = \sigma_a^{23}.\end{aligned} \tag{4}$$

These quantities appear as generalized forces. The rate of dissipation of mechanical energy per unit volume is determined by the expression

$$\dot{d} = \sum_{i=1}^{6} \sigma_i \dot{\varepsilon}_i + 0,5 \sum_{x=1}^{4} \tau_x \dot{\gamma}_x. \tag{5}$$

Here $\dot{\varepsilon}_1, \ldots, 0.5\dot{\gamma}_4$ are the rates of the generalized variables. Using (3) and the associated rule of deformation [1], we can determine the rate of the generalized displacements. Solving the system thus obtained relative to the generalized forces, we find

$$\begin{aligned}&\sigma_i^j = [(1/2\dot{\lambda})\sum_{k=1}^{6} \delta_{ik}\dot{\varepsilon}_k - \Delta_i]_j / \Delta_j, \quad i = \overline{1,6};\\ &\tau_k^j = [(1/4\dot{\lambda}\theta)\sum_{i=1}^{4} \rho_{ki}\dot{\gamma}_i]_j, \quad k = \overline{1,4}.\end{aligned} \tag{6}$$

Here, $\Delta_\varphi = \det A_j$; $\theta_j = \det C_j$; Δ_{ij} are the determinants obtained by replacing column i of D_j by the vector $\vec{B}_j$; $d_{jik} = d_{jki}$ are the algebraic complements of element (i, k) D_j; $p_{jki} = p_{jik}$ are the same for element qj. Substitution of (6) into (3) allows us to express $\dot{l}_j \geq 0$ through the rate of the generalized displacements. Let us assume that the values of $\dot{\gamma}^{jk}$ are constant within

limits of layer j, while the linear distribution is correct for $\dot{\varepsilon}_{ji}$ through the thickness of the packet:

$$\dot{\varepsilon}_i^j = \dot{e}_i - z\dot{æ}_i \; . \qquad (7)$$

The running forces and moments applied to So:

$$T_i = \sum_{j=1}^{n} \int_{z_{1j}}^{z_{2j}} \sigma_i^j dz, \quad Q_K = \sum_{j=1}^{n} \int_{z_{1j}}^{z_{2j}} \tau_K^j dz, \quad M_i = \sum_{j=1}^{n} \int_{z_{1j}}^{z_{2j}} \sigma_i^j z\, dz. \qquad (8)$$

Here i = $\overline{1,6}$, K = $\overline{1,4}$. Substitution of (6) into (8) considering (7) yields

$$T_i = \sum_{j=1}^{n} \Big[\frac{1}{2} \sum_{K=1}^{6} \delta_{iK}^j (I_{1j}\dot{e}_K - I_{2j}\dot{æ}_K) - \Delta_{ij} h_j\Big]/\Delta_j \; ,$$

$$M_i = \sum_{j=1}^{n} \Big[\frac{1}{2} \sum_{K=1}^{6} \delta_{iK}^j (I_{2j}\dot{e}_K - I_{3j}\dot{æ}_K) - \Delta_{ij} h_j z_j\Big]/\Delta_j \, , \; i = \overline{1,6}; \qquad (9)$$

$$Q_K = \frac{1}{4} \sum_{j=1}^{n} \Big(\sum_{i=1}^{4} \rho_{Ki}^j \dot{\gamma}_i^j \Big) I_{1j} / \theta_j \, , \quad K = \overline{1,4}.$$

Here hj = $z_{2j} - z_{1j}$ is the thickness, z_j is the coordinate of the mean surface of layer j. The integrals I_{ij} are computed by the expression

$$I_{ij} = \int_{z_{1j}}^{z_{2j}} (z^{i-1}/\dot{\lambda}_j)\, dz, \quad i = \overline{1,3}. \qquad (10)$$

Equations (9) are parametric equations of the limiting surface for multilayer composite plates and shells with variable loading. We have used the equations produced to solve the problem of the limiting state of a cylindrical shell.

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UDC 539.3.519

ESTIMATE OF LOAD-BEARING CAPACITY BASED ON GENERAL STABILITY OF METAL-PLASTIC CYLINDRICAL GRID-STRUCTURE SHELLS

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This article studies a method for estimating the load-bearing capacity based on the general stability of cylindrical metal-plastic grid-structure shells. Results are presented from analysis of the effectiveness of this type of structure upon variation of the basic geometric parameters of the grid structure and the elastic properties of the material.

One promising grid-structure design consists of cylindrical shells in which the grid structure, reinforced by external heterogeneous layers, is formed by a system of crossing spiral and circular ribs.

The structural advantage of metal-plastic shells over purely grid-type shells is the possibility of creating sealed products, as well as the simpler process equipment required for manufacture.

The method of computing the total stability of these structures is based on a continual model within the framework of the classical theory of shells.

Let us study a multilayer cylindrical shell, articulated at its ends, of length L and radius R, loaded by a combination of loads. We shall utilize well-known static relationships for moment shells of rotation and geometric equations for small deformations in order to create a method for the required computations. The physical equations can be represented as a set of membrane, mixed, flexural and shear rigidities of the shell, computed considering the structural height of the grid and the coordinates of each layer.

Representing the solution in the form of double trigonometric series, we obtained a system of solution equations as follows:

$$[B] \times [UVWFE]^{-1} = [OOPOO]^{-1},$$

Here the matrix [B] is the matrix formed by the generalized rigidities of the cylindrical shell;

$[UVWFE]^{-1}$ is the column matrix of the amplitude values of displacements and angles of rotation;

$[OOPOO]^{-1}$ is the column matrix of loads.

Like the displacements, the load was represented as a double trigonometric series. The complex of loads consisting of the bending moment, shear force and axial compressive load, was reduced by simple transforms to the axial component of the compressive force.

The membrane, bending, mixed and shear rigidities included in the coefficients of matrix [B] were obtained for a cylindrical shell consisting of a laminar material [1]. The expressions for these rigidities were represented in integral form including, within the limits of integration, the coordinate of the initial surface. As a new variable was introduced, in which the new coordinate was computed from the inner surface, the expressions for the rigidities were converted to integral form in which within the limits of integration only the thickness of the layer was included. Subsequent transforms were used to analyze the case in which it is necessary to consider changes in the metric properties through the thickness of the material. The laminar nature of the structure presumes that the rigidity coefficients are piecewise-continuous functions of the coordinates of a layer of the structure. Integrating with respect to sectors and representing the logarithmic functions obtained by exponential series, we obtain relationships for computation of rigidities which are easily embodied in algorithms.

The results of [2, 4] were used to calculate the rigidity coefficients of a layer of a cylindrical envelope of heterogeneous and grid structure.

The entire complex of algorithms developed was implemented on a YeS-1055 computer in the form of standard subroutines written in the programming language FORTRAN-IV.

The influence of the basic geometric parameters of the layers of a cylindrical shell and the physical properties of the materials on the load-bearing capacity was analyzed. Figure 1 shows a characteristic curve of the variation in load-bearing capacity as a function of angle of a spiral grid layer ϕs. The upper curve describes the behavior of the metal-plastic shell, while the lower describes the behavior of the shell without the metal. Figure 2 shows the variation of the influence of metal thickness in the investigation of a metal-plastic shell.

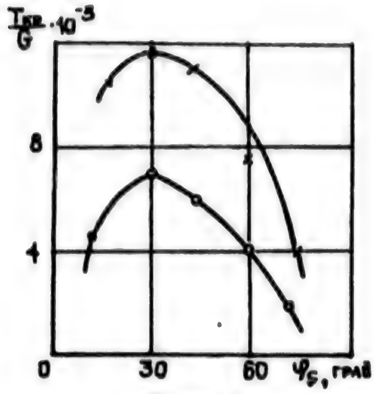

Figure 1

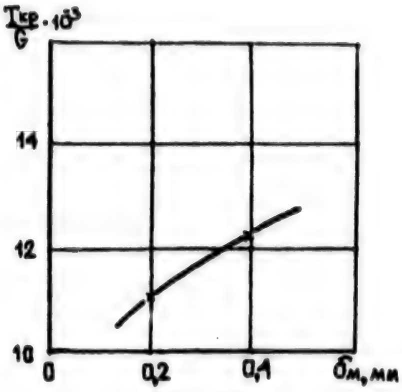

Figure 2

The parametric analysis we have performed allows us to estimate the influence of the basic geometric parameters of a cylindrical shell on load-bearing capacity and select the optimal version of a structure.

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UDC 539.3

NONLINEAR DEFORMATION OF ANISOTROPIC SHELLS OF ROTATION UNDER AXISYMMETRICAL LOADING

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A study is made of elastic systems of a sequence of coaxial multilayer shells of rotation assembled of anisotropic layers with thickness variable along the generatrix. At each point on the shell there is one plane of elastic symmetry, parallel to its coordinate surface. The loads acting on the elastic system are such that it is deformed while preserving axial symmetry. In the study of the stress-strain state of such shell systems, the initial equations are the geometrically nonlinear equations of the theory of thin shells in the quadratic approximation, based on the Kirkhoff-Love hypothesis for the entire packet of layers. In this case the system of initial equations is reduced to a system of eight ordinary nonlinear differential equations such as [1]:

$$\frac{d\bar{N}}{dt^j} = A(t^j)\bar{N} + \bar{\Phi}(t^j,\bar{N}) + \bar{f}(t^j)$$
$$(t^j_{j-1} \le t^j \le t^j_j; \quad j = 1, 2, \ldots, p), \quad (1)$$

where

$\bar{N} = \{u_x, u_z, v, \vartheta_s, N_x, N_z, \hat{S}, M_s\}^T$; u_x, u_z, v – are the radial, axial and tangential displacements; θ is the angle of rotation, N_x, N_z, $\hat{s}$ are the radial, axial and shear forces; M_s is the bending moment; A is a matrix, $\bar{\Phi}$ is a nonlinear vector function, $\bar{f}$ is a vector column; p is the number of sections of the elastic system, t^j is the integration variable in sector j. To formulate the boundary-value problem we must assign four boundary-value conditions on each contour

$$\bar{g}_1(\bar{N}(t^1_0)) = 0; \qquad \bar{g}_2(\bar{N}(t^p_p)) = 0. \quad (2)$$

According to the form or structure, the elastic system is divided into a sequence of shells of canonical form and in each sector the integration variable tj is introduced which is convenient for description of the geometry of that sector.

This selection of decision functions allows uniform description of the entire class of shells of rotation, including a circular plate and a cylindrical shell, permits formulation of the boundary-value conditions in force-moments, displacements and in mixed form, allows the simplest matching of shells of different types. The solution of the boundary-value problem (1), (2) also describes the stress-strain state of elastic systems of orthotropic material, in which the main directions of elasticity do not coincide with the coordinate lines, which occurs, e.g., upon manufacture of structural shell elements by winding.

The numerical solution of boundary-value problem (1), (2) is based on effective joint utilization of the method of linearization and the method of discrete orthogonalization, which allows the algorithm to be implemented as an application software package [2].

The deformation of the elastic system (Figure 1) from the conical shell ($r = 3.873z + 136.2$), a parabaloid of rotation ($r = 100\text{-}0.097z^2$) and a cylindrical shell ($r = 100$) under the simultaneous influence of internal pressure q_0 and compressive axial force Q_0 were studied. The boundary conditions at the contours z = z10 and z = *z33* are fixed as:

$$u_x = \vartheta_s = \hat{S} = 0, \; N_z = Q_0 \quad \text{where} \quad z = z^1_0$$
$$u_x = u_z = v = \vartheta_s = 0 \quad \text{where} \quad z = z^3_3$$

An elastic system was prepared of an orthotropic material, the direction of reinforcement of which forms angle ψ with the generatrix ($\sin\psi = c/r$). The value of c is determined by the initial angle ψ_0 at the contour $z = z^1_0$. The elastic characteristics of the material in the system of coordinates of the main directions of elasticity are as follows: $E1 = E_0 = 0.75 \cdot 10^6$; $E_2 = 1/3E_0$; $G_{12} = 1/12E_0$; $\nu_1 = 0.2$. The thickness changes as $h = 20/r$.

Figure 2 shows the variation in axial displacement of the contour $z = z^1{}_0$ with axial force Q_0 for two values of initial reinforcement angles $\psi_0 = p/6$ (solid line) and $y_0 = p/2$ (dash line) in the subcritical and initial supercritical stage of deformation with various values of internal pressure θ_0. Figure 3 shows the distribution of bends w along the z axis where y0 = p/6 and $q_0 = 2$. The number 1 represents the distribution of the bend at the upper limiting point (Q_0

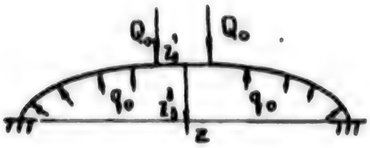

Figure 1

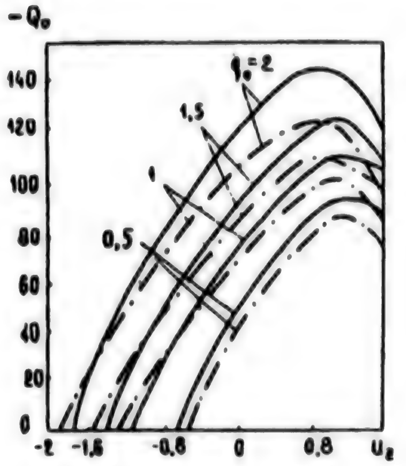

Figure 2

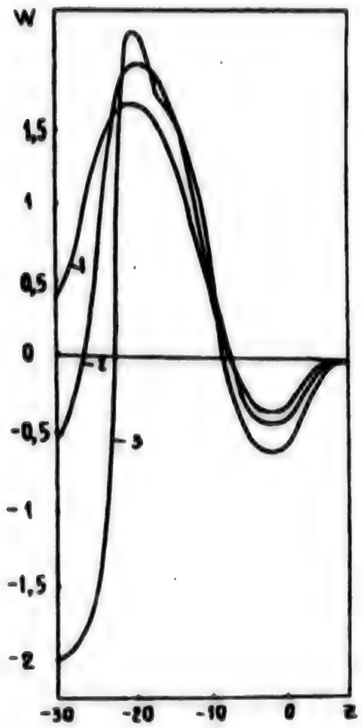

Figure 3

$= -141$), while the numbers 2 and 3 refer to $Q_0 = -10$ in the subcritical and supercritical areas of deformation.

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UDC 539.3

THE INFLUENCE OF THE STRUCTURE OF LAMINAR HOLLOW SPHERES ON THEIR DYNAMIC CHARACTERISTICS

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In designing elements for structures of composite materials, it is important to predict their dynamic properties as a function of their configuration, distribution of masses, elastic properties of the materials, et cetera. This article presents a numerical analysis of the influence of the structure of laminar hollow spheres on their dynamic characteristics in a three-dimensional statement. The use of the three-dimensional theory of elasticity, in contrast to two-dimensional theories, allows us to reflect the specifics of the behavior of laminar elastic bodies.

The problem of free, asymmetrical oscillations of hollow spheres consisting of transversely isotropic layers of constant thickness in rigid contact with each other is studied on the basis of equations from the three-dimensional theory of elasticity.

The method of solving this problem is based on reducing the initial three-dimensional problem by separation of variables using spherical functions to a sequence of one-dimensional problems for determination of the eigenvalues with respect to a radial coordinate. These one-dimensional problems are then solved numerically by stepwise search and an orthogonal sweep [1].

Using three-layer spherical shells as an example, the variation in frequency characteristics is studied as a function of two factors — the relative thickness of the component layers and their placement. In the first case, the relationship between thicknesses of symmetrically placed layers is determined by the expression

$$\delta = \frac{2h_{\text{н}}}{h_{\text{з}} + 2h_{\text{н}}}, \quad (H = 2h_{\text{н}} + h_{\text{з}} = \text{const})$$

where H, h_h and h_3 represent the thickness of the entire sphere, the load-bearing layers and the filler. In Figure 1 (a, b) the solid lines show the variation of the first three frequencies with parameter δ with ratios H/R of 0.1 and 0.4. The Roman numerals here represent the ordinal number of the oscillating frequency, while the Arabic numerals show the value of n representing the wave formation of the sphere. As we can see from the figure for spherical shells of moderate thickness (H/R = 0.1) throughout the entire range of change of $\delta \in (0, 1)$ each frequency is represented by one wave-formation parameter. For rather thick spheres (H/R = 0.4), the graphs obtained (Figure 1b) have break points resulting from a change in the shape of wave formation, as well as the transition from oscillations of the second class to oscillations of the first class [2] and vice versa. In the second example we define the variation of lower frequencies of the laminar sphere in question with the placement of the component layers, represented by the parameters

$$\Delta = \begin{cases} \dfrac{h_{\text{ж}1}}{2(h_{\text{ж}1} + h_{\text{ж}2})}, & H = h_{\text{м}} + h_{\text{ж}1} + h_{\text{ж}2} = \text{const} \\ 0.5 + \dfrac{h_{\text{м}1}}{2(h_{\text{м}1} + h_{\text{м}2})}, & H = h_{\text{ж}} + h_{\text{м}1} + h_{\text{м}2} = \text{const}, \end{cases}$$

where

$$(h_{\text{м}i}\ (i = 1, 2), \quad h_{\text{ж}i}\ (i = 1, 2))$$

are the thicknesses of the layers of the soft and hard materials, respectively. The interval of change $\Delta \in (0, 0.5)$ correspond to a three-layer spherical shell with hard outer layers, while where $\Delta \in (0.5, 1)$ the material of the outer layers is soft. Figure 2 (a, b) shows the variation of the lower frequencies (solid lines) with the parameter for the ratios H/R = 0.1, 0.4. Here, as in the first example, the mutual placement of the hard and sort layers has a significant influence on natural frequencies of the three-layer spheres where H/R = 0.4. These same problems were also solved on the basis of approximate theories: the classical and refined theories of Timoshenko (dash and dot-dash lines). The studies performed showed that for thickwall hollow spheres the variation in their dynamic characteristics as a function of structure is quite complex, not always sufficiently reflected by two-dimensional approximate theories.

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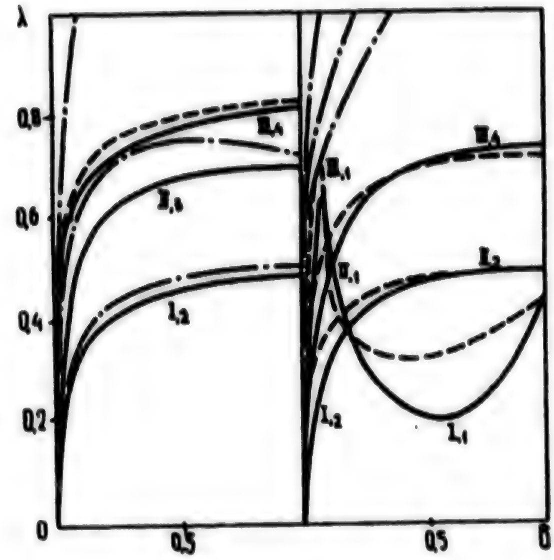

Figure 1

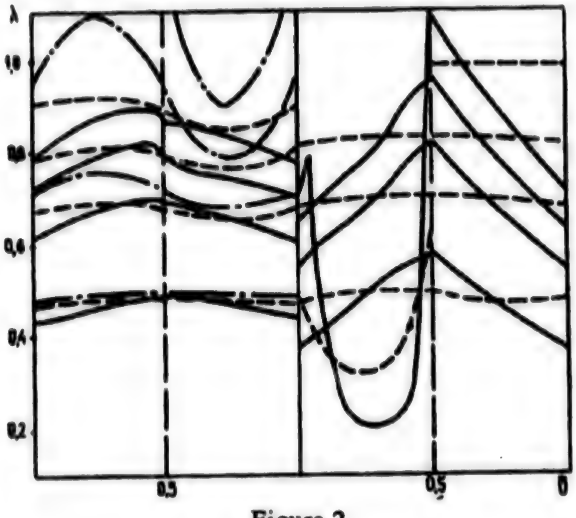

Figure 2

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UDC 539.3

SOLUTION OF PROBLEMS OF STATICS OF COMPOUND REINFORCED SHELLS OF ROTATION IN A REFINED STATEMENT

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A study is made of the problem of determining the stress-strain state of compound reinforced shells of rotation assembled of rigidly coupled anisotropic layers of variable thickness in a refined statement. It is assumed that the hypothesis of the straight element can be accepted for the entire packet of the shell. According to this hypothesis, a straight element initially perpendicular to the coordinate surface before deformation, remains straight after deformation, but is no longer perpendicular to the deformed surface, and its length does not change. The material of the layers of the shell generally has one plane of elastic symmetry, leading to the fact that in the elasticity equations the quantities representing extension and bending are interrelated with the factors of shear and twisting, as a result of which the problem of determining the stress-strain state of such shells is significantly complicated.

The solution of the problem of statics for this class of shells in the coordinate system S, θ (S is the length of an arc of the meridian, θ is the central angle in the parallel circle) after isolation of variables by means of Fourier series on the circumferential coordinate θ, for each harmonic number k is reduced to integration of a system of ordinary 20th-order differential equations such as [1]

$$\frac{d\bar{N}}{ds} = A(s)\bar{N} + \bar{q};$$

$$\bar{N} = \{N_{r,k}, N_{z,k}, N_{s\theta,k}, M_{s,k}, M_{s\theta,k}, u_{r,k}, u_{z,k}, v_k, \psi_{s,k}, \psi_{\theta,k}, N'_{r,k}, \dots, \psi'_{\theta,k}\};$$

$$A(s) = \|a_{i,j}(s)\| \quad (i, j = 1, 2, \dots, 20); \quad q = \{q_1, q_2, \dots, q_{20}\},$$

where Nr, NM are the radial and axial forces, u_r and uz are the corresponding variables, NsMθ is the shear force, M_s is the bending moment, Msθ is the twisting moment, s is the shear displacement, ψ_s and ψ_e are the body angles of rotation of the linear element.

For the particular case of axisymmetrical deformation of shells (k = 0) we have a tenth order system of equations. In the case of orthotropic shells, the main directions of elasticity of the material of which coincide with the directions of coordinate lines, the system obtained is broken down into two independent systems of equations, each of tenth order.

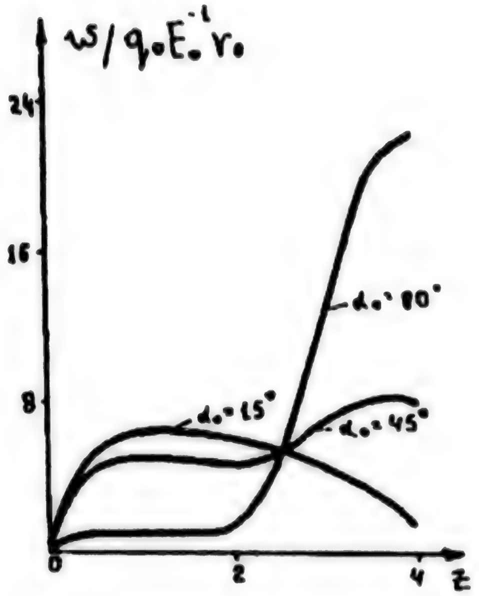
The solution of the boundary-value problems for the system of equations thus obtained is performed by means of a stable numerical method of discrete orthogonalization, assuring high accuracy of the results produced [2]. A solution algorithm has been developed for this class of problems and implemented on a computer, allowing us to determine the stress-strain state of anisotropic shells of rotation considering the variability of their geometric and mechanical parameters.

As an example, we have analyzed the problem of determining the stress-strain state of a two-layer elastic system, the left portion of which is a cylindrical shell with radius r = r1 and thickness h0, while the middle surface of the right portion is formed by rotating the parabola r = a + bz + cz2 (z1 $\le$z $\le z_2$) about the 0z axis, where the constants a, b, c were selected so that at the point of conjugation of the function r and dr/dz there is no discontinuity, and also so that at the right end the radius of the shell is r = r2. The distance between the ends is l, and z2 = l. The shell is generated by winding tape made of an orthotropic material with the following elastic characteristics: $E_1 = 20.1\ E_0$, $E_2 = 1.6\ E_0$, $\nu_{12} = 0.024$, $G_{23} = 0.548$ E0, $G_{12} = G_{13} = 0.878\ E_0$, and is influenced by axisymmetrical internal pressure varying as

$$q_r = \begin{cases} q_0 & \text{where} \quad 0 \le z \le z_1 \\ q_0(2 - 2z/l) & \text{where} \quad z_1 \le z \le z_2 . \end{cases}$$

Winding was performed on geodetic lines, with the inner layer wound at angle α, the outer layer at angle $-\alpha$.

In the calculations we assumed: l = 4, r1 = r_0, $r_2 = 1.5\ r_0$, $h_0 = 0.1\ r_0$, $z_l = l/2$. We should note that in this shell, when it is exposed to an axisymmetrical load, the circumferential displacement s occurs, shear force $N_s\theta$ and torque $M_s\theta$ arise, the main directions of elasticity in the material of the shell coincide with the directions of the coordinate lines.



The figure shows the change over the length of the shell in bend w for certain values of α_0 — the angle between the tape and the meridian in the cylindrical portion of the shell. The table also shows the values of stresses σ_1, σ_2 acting along the main directions of elasticity for certain values of α_0, as well as the shear stresses σ_{12} arising in the tape at the outer surface of the envelope near a seal.

α0, degrees	15	30	45	60	80
σ_1/θ_0	-41.16	-21.90	-11.01	-16.15	-7.913
σ_2/θ_0	-10.53	-33.58	-50.92	-40.11	-17.42
σ_{12}/θ_0	-17.39	-21.71	-7.751	-5.063	-0.7721

The data we have presented allow us to conclude the essential variation of bend angle w and stresses σ_1, σ_2 and σ_{12} with reinforcement angle.

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METHOD OF DESIGNING METAL-COMPOSITE JOINTS

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Beam structures of composites are now widely used in various areas of engineering. However, the creation of highly effective joints between elements in such structures is a complex problem, still awaiting its solution. In this article, we suggest a calculation plan considering the essential heterogeneity of the physical-mechanical characteristics of a joint in these materials. The joint section is looked upon as a three-layer thickwall cylindrical shell with layers of variable thickness. One of the layers of the shell is metal, the other two model composite layers with longitudinal and transverse layup.

Following the results of [1], we obtain for the model selected a solution system of equations and natural boundary conditions. Considering the material of the envelope to be orthotropic, a perpendicular to the initial surface to be incompressible, we write equations for the axisymmetrical problem of the theory of elasticity

$$\begin{cases} (H_2 \sigma_1)_{,1} + (H_2 \tau_{13})_{,3} = 0 \\ (H_2 \sigma_3)_{,3} - K_2 \sigma_2 + (H_2 \tau_{13})_{,1} = 0 \end{cases} \quad (1)$$

$$\sigma_{1;2} = \bar{E}_{1;2}(\varepsilon_{1;2} + \mu_{12;21}\varepsilon_{2;1}); \; \tau_{13} = G_{13}\varepsilon_3 \quad (2)$$

$$\varepsilon_1 = U_{1,1} \; ; \; \varepsilon_2 = \frac{A_2 K_2 U_3}{H_2}; \; \varepsilon_3 = U_{3,3} \quad (3)$$
$$\varepsilon_{13} = U_{1,3} + U_{1,1}$$

From equations (2) and (3) we have $U_3 = W_0(d_1)$ and

$$U_1 = -W_{0,1}\gamma + \int_0^\gamma \frac{\tau_{13}}{G_{13}} d\gamma + f(\alpha_1) \quad (4)$$

To construct a kinematic model we shall assume that the stresses τi_{13} *change through the thickness of layer i (the layer is homogeneous in thickness) and are equal to the mean stresses*

$$\tau_{13}^i\left(\alpha_1, \gamma = \frac{h_i + h_{i-1}}{2}\right) = \tau_i(\alpha_1) \quad (i = 1,2,3) \quad (5)$$

Defining the arbitrary constant $f(\alpha 1)$ from the condition $U_1 = U_0(\alpha_1)$, where U0 is the axial displacement of the initial surface, we obtain from (5) for layer i

$$U_1^i = U_0(\alpha_1) + \sum_{j=1}^{i-1} \delta_j \psi_j + (\gamma - h_{i-1})\psi_i \quad (6)$$

where

$$\psi_j = -W_{0,1} + \frac{\tau_j}{G_{13}^j} \; ; \; \delta_j = h_j - h_{j-1} \; . \quad (7)$$

The relative deformations in the layers can be determined according to equations (3) and (6), while the stresses in the layers can be determined from the physical relationships (2).

Let us find the transverse stresses τ^{i13} and σ_{i3}. *For this purpose, we integrate the equilibrium equations (1) with respect to* $\alpha 3 = \gamma$, and express the arbitrary functions thus produced through the loads on the outer surface of the shell, from the condition $\tau^i_{13}(\alpha_1, \gamma = 0) = 0$; $\sigma 13\,(\alpha 1, \gamma = 0) = -p1(\alpha 1)$.

We obtain

$$\tau_{13}^i = \frac{1}{H_2}\left(-\sum_{j=1}^{i-1}\int_{h_{j-1}}^{h_j} H_2 \sigma_{1,1}^j d\gamma - \int_{h_{i-1}}^{\gamma} H_2 \sigma_{1,1}^i d\gamma\right) \quad (8)$$

$$\sigma_3^i = \frac{1}{H_2}\left[-p_1 + \sum_{j=1}^{i-1}\int_{h_{j-1}}^{h_j}(K_2\sigma_2^j - H_2\tau_{13,1}^j)d\gamma + \int_{h_{i-1}}^{\gamma}(K_2\sigma_2^i - H_2\tau_{13,1}^i)d\gamma\right] . \quad (9)$$

The stresses (8) and (9) should satisfy the static boundary conditions on the outer surface of the shell $\gamma = h_3(\alpha_1)$. Introducing the coordinates $\alpha'1$, $\alpha'2$, α'_3, we shall have $\tau 1'3'(\alpha_1, \gamma = h3) = 0$; $\sigma 3.(\alpha_1, \gamma = h_3) = -P_2(\alpha_1)$. Going over from $\tau 1'3'$, $\sigma 3'$ to $\tau 13$ and $\sigma 3$ by means of the known equations for rotation of stress tensor components and considering that the angle θi is so small that we can assume $\sin \theta i$ ' θi, $\cos \theta i$ = approximately 1, and we finally obtain

$$\begin{cases} \tau_{13}^3(\alpha_1, h_3) - h_{3,1}\sigma_1^3(\alpha_1, h_3) = p_1 h_{3,1} \\ \sigma_3^3(\alpha_1, h_3) - h_{3,1}\tau_{13}^3(\alpha_1, h_3) = p_1 - p_2 . \end{cases} \quad (10)$$

Substituting expressions (8), (9) for $i = 3$ into equations (10), we can write two equations for the solution system. The remaining equations are obtained from (5), (7) as

$$\tau_{13}^{i}\left(\alpha_1, \gamma = \frac{h_i + h_{i-1}}{2}\right) = G_{13}^{i}\left(\varphi_i + W_{0,1}\right). \quad (i = 1,2,3) \qquad (11)$$

Here the left portion is determined by equation (8). Thus, we have obtained a system of five equations (10), (11), including the two variables U_0, W_0 as unknowns plus three angles of rotation of the normal in the layers $\varphi 1$, φ_2, $\varphi 3$. The equations of the system are moment equations and consider the variable metrics and thickness of the shell and the transverse shear deformation in the layers.

The corresponding system of boundary-value conditions is obtained by a variational method. The geometric conditions at the edge α_1 = const are formulated through the kinematic variables U0, W0, φi (i = 1, 2, 3), while the corresponding static conditions are obtained through the axial force N, the shear force Q, the bending moments in the layers Mi, which are

$$N = \sum_{j=1}^{3} \int_{h_{j-1}}^{h_j} H_2 \sigma_2^j d\gamma \; ; \; Q = \sum_{j=1}^{3} \int_{h_{j-1}}^{h_j} H_2 \tau_{13}^j d\gamma$$

$$M_i = \int_{h_{j-1}}^{h_j} H_2 \sigma_1^i (\gamma - h_{i-1}) d\gamma + S_i \sum_{j=i+1}^{3} \int_{h_{j-1}}^{h_j} H_2 \sigma_2^j d\gamma, \qquad (12)$$

This solution system was used to obtain certain qualitative results concerning the influence on stress-strain state of a joint of the thickness of the circular winding, the half-aperture angle of the cone at the metallic tip and the rigidity of the individual layers.

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DESIGN OF PRESSURE VESSELS OF TWO-LAYER STEELS

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The applicable standards and technical documents for the design of pressure vessels (e.g., GOST 14249-80) require the design of pressure vessels manufactured of two-layer steels to be performed based on the characteristic mechanical properties of the base metal. It is considered that the cladding layer, while providing corrosion resistance, also provides an additional strength reserve. Its thickness is not considered in the computations.

However, some cases of failure of bimetallic pressure vessels [1] have shown that this approach is erroneous for estimating the strength of two-layer steel structures. This is because the two-layer steel is actually a composite material consisting of the metal of the base layer, the carbide-saturated zone in the metal of the cladding layer, the metal of the cladding layer itself, with its inherent effect of deformation interaction of the components [2, 3]. The interaction of the layers, which have dissimilar physical properties, during joint deformation results in the fact that the failure of two-layer steels starts with the formation of microscopic cracks in the carbide-saturated zone of the cladding metal, which is the strongest and least ductile component of the composite. These microscopic cracks are the initial foci of failure, the development of which leads to failure of the cladding layer and of the entire structure, which has been observed in practice [1].

The introduction of a layer of nickel to the area where the two steel layers join, in order to eliminate the structural heterogeneity, does not always solve the problem, due to the presence of a large number of cracks in the nickel layer, formed during manufacture of the two-layer steel. Failure of two-layer steel with an intermediate layer of nickel also starts with the formation of microscopic cracks in the carbide-saturated zone of the cladding layer at the location of defects in the nickel layer.

This mechanism of failure of two-layer steels has been verified metallographically in a number of steel samples manufactured by Soviet industry during static tensile testing and short-cycle fatigue testing in pulsating extension at 29-475 ° C, and in static bend testing. Tests of the specimens have shown that the deformation at which microscopic cracks are detected is determined by the composition of the two-layer steels, the loading conditions and the test temperature. Microscopic cracks are not formed in two-layer steels with a layer of nickel if there are no defects in the nickel layer and if the two-layer steel delaminates during deformation, which occurs where the bond between the layers is weak. If the two-layer steel delaminates, the microscopic cracks formed in the carbide-saturated zone of the cladding layer result only in failure of the cladding layer, while complete failure of specimens occurs when the ductility of the base metal is exhausted.

Results of these tests show that the ductility and short-cycle strength characteristics of two-layer steels (with strong bonding between layers and the presence of a carbide-saturated zone in the cladding metal, which is true in most cases) are less than the characteristics of the base metal, by which strength and low-cycle fatigue calculations are recommended. The influence of microscopic cracks on the characteristics of short-cycle fatigue is particularly great — the short-cycle fatigue curves of a bimetal are significantly below the curves for the base metal of a two-layer specimen throughout the entire temperature range studied.

The structural heterogeneity of two-layer steels and the related specifics of their failure indicate the need for calculation of the strength and short-cycle fatigue of structures of two-layer steels by methods which allow for the possibility of elastic-plastic deformation (if only in areas of stress concentration) not based on the characteristics of the base metal, but rather based on the deformation criteria of failure [4]. The limiting deformation in this case should be the deformation of formation of microcracks, with some strength reserve, allowing serious errors to be avoided. The maximum permissible deformation of two-layer steels can be determined by testing of specimens of the actual thickness to be used with the cladding layer present or proportionally thinner specimens for which the cladding layer and the base metal

of the two-layer specimen are reduced mechanically while preserving the initial ratio of thickness of the layers, which is necessary to retain the effects of deformation interaction of the components of the composite.

For two-layer steel with the composition 16 GS steel + 008Kh13 steel (the most widely used in the manufacture of petrochemical equipment) at temperatures of 20-475 ° C, microscopic cracks are detected with residual deformation 10-12%.

The deformation approach here suggested for solution of the problem of determining the strength of structures consisting of two-layer steels was used to estimate the residual operating life of deformed petrochemical equipment, and its practical application has shown that it is correct.

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539.3

TWISTING OF A PLASTICALLY HETEROGENEOUS ROD OF CIRCULAR CROSS SECTION

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A study is made of a rod of circular cross section of radius a. Suppose the lower end of the rod is fixed, while the z axis is directed along the axis of the rod; the rod is twisted by torque M0. The problem is solved by the inverse method of St. Venant on the assumption that the transverse cross sections remain flat even beyond the elasticity limits of the deformed material [1]. The Mises creep condition is accepted in the plastic zone

$$\tau_z = K(z), \tag{1}$$

where τz are the shear stresses, directed at each point in the cross section perpendicular to the radius, and are functions of the distance from the center of the cross section to the point in question, k(z) is the creep limit of the material in shear — a variable plastic constant [2].

Here

$$K(z) = K + \frac{K_0 - K}{a^n}(z^n - z_0^n), \tag{2}$$

where r0 is the radius of the elastic core. At the boundary of the elastic core, k(r0) = ; k_0 is the plastic constant for r = a, when all cross sections are in the state of creep (k k_0).

Considering this, the distribution of the stresses will be

$$\tau_z = \begin{cases} K\,\dfrac{z}{z_0} & a \le z \le z_0 \\ K(z) & z_0 \le z \le a \end{cases}. \tag{3}$$

We note that the solution of this problem where $k_0/k = 1$ coincides with the solution of the previously known problem [1].

The stresses of (3) satisfy the equations of equilibrium and the equations of continuity of deformation. The conditions of continuity at the boundary between the elastic and plastic zones (where $r = r_0$) are met. On the side surface the shear stresses based on the rule of parity of shear stresses introduce no component, which corresponds to absence of surface loads here. Consequently, the boundary conditions are also met on the side surfaces of the rod.

Let us study the boundary conditions at the ends. Here the shear stresses τz should balance the external moment M0, i.e.,

$$M_0 = \int_F \tau_z \cdot z \cdot dF \tag{4}$$

Let us divide the area of integration F into the elastic zone fyn and the plastic zone Fnn. Substituting into equation (4) the values of stresses from (3) corresponding to these zones, we obtain

$$M_0 = \frac{K}{z_0}\int_{F_{yn}} z^2\, dF + \int_{F_{nn}} K(z)\cdot z\, dF, \tag{5}$$

where the area of a ring of infinitely small thickness is taken as an elementary area

$$dF = 2\pi z\, dz. \tag{6}$$

Substituting (6) and (2) into (5) and integrating, we obtain

$$M_0 = \frac{\pi K}{6}(4a^3 - z_0^3) + 2\pi(K_0 - K)a^3\left\{\frac{1}{n+3} - \frac{1}{3}\left(\frac{z_0}{a}\right)^n + \frac{n}{3(n+3)}\left(\frac{z_0}{a}\right)^{n+3}\right\} \tag{7}$$

Assuming that the limiting state of the twisted rod occurs when the plastic zone encompasses the entire cross section (i.e., where r0 = 0), we can use equation (7) to find the limiting torque

$$M_0^T = \frac{2}{3}\pi a^3\,\frac{K_n + 3K_0}{n+3}. \tag{8}$$

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III. STUDY OF PROPERTIES OF COMPOSITE MATERIALS

UDC 539.4.001:678.067.5

ESTIMATING INELASTICITY PROPERTIES OF FIBER COMPOSITE MATERIALS

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Most of the basic mechanical properties of structural materials are structure-sensitive. This is particularly true of the characteristics of strength and ductility, which follows, e.g., from analysis of the Patch-Hall equation, determining the critical flow stress σ from the resistance to dislocation σ_0 in the body of an individual structural element in the free (nonconstricted) state, its characteristic dimension d, as well as the resistance to transmission (translation) of deformation through a division boundary, determined by the parameter ky:

$$\sigma = \sigma_0 + K_y d^{-m} \quad . \qquad (1)$$

The formation of the specific structure of a metal as it is produced in the process of transition from the liquid to the solid state and in subsequent traditional technological processes (such as heat treatment) cannot satisfy the demands of practice, which has stimulated in recent years the search for the expedient "artificial" creation of an optimal regular structure of elements of varying strength and ductility alternating in a certain sequence, permanently joined together at their division boundaries — composite materials.

The purpose of this work is to develop characteristics of composite materials determining their resistance to the transition from elastic to plastic deformation on the example of a fiber composite material in the following system: strong, rigid boron fibers, bound in a soft aluminum matrix. Particular attention is given to small inelastic deformations, the development of which under load is the prime cause of dissipation of energy in the material under cyclical loads and accumulation of irreversible fatigue damage, leading finally to the development of cracks and failure. This requires that we introduce to the practice of estimating the intensity of development of inelastic deformations an individual characteristic of composite materials, a structurally sensitive parameter allowing us to describe the shape and size of the mechanical hysteresis loop.

It is characteristic for composite materials that, on the one hand, the deformation resistance is greater than the value computed according to an additive rule [1], while on the other hand inelastic (microplastic) deformation starts earlier (practically at $\sigma w \rightarrow 0$), as a result of deviations from Hooke's law. As an example, Figure 1 shows a diagram of the extension of a fiber composite material and the development of the hysteresis loop in the course of deformation and unloading.

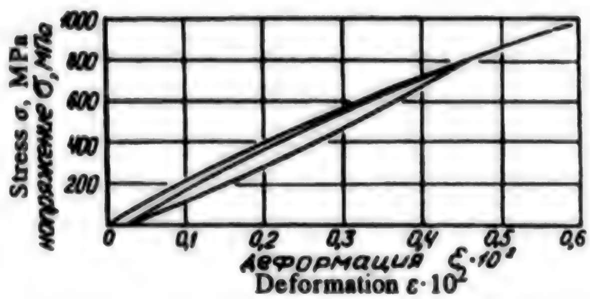

Figure 1. Diagram of Extension of Fiber Composite and Formation of Mechanical Hysteresis Loops

Let us study a model of a solid deformable body [2], consisting of high-strength "elastic" boron fibers placed regularly in the direction in which external force is applied, occupying relative volume ν_{BY}, having normal elasticity modulus EB and experiencing stress σ_{BY}. The matrix filling the space between the fibers and inseparably bonded to the surfaces of the fibers supports compatibility of deformation of the entire composite. Since the matrix metal is a polycrystalline substance consisting of crystals — grains, each of which has anisotropic elastic, strength and plastic

properties, a certain field of internal stresses arises in the process of loading [3]. At any instant of loading the matrix will contain relative volumes ν_{MY} and ν_{M}, which are elastically and plastically deformed, experiencing local stresses σ_{MY} and $\sigma_{M\Pi}$. The condition of equilibrium of the force increment projected onto the geometric axis of the specimen becomes:

$$d\sigma = \nu_B \, d\sigma_B + (\nu_M - \nu_{M\Pi}) \, d\sigma_{MY} + \nu_{M\Pi} \, d\sigma_{M\Pi} \; . \tag{2}$$

The intensity of entry of the "soft" matrix into plastic deformation is determined by a function of stress σ_{BY} on the elastic fibers, which can be conveniently expanded into a series

$$\frac{d\nu_{M\Pi}}{d\sigma_{BY}} = f(\sigma_{BY}) = \frac{a}{M} + b\left(\frac{\sigma_{BY}}{M}\right) + c\left(\frac{\sigma_{BY}}{M}\right)^2 + \dots \tag{3}$$

An experimental check of the basic aspects of this fiber composite material model for a system consisting of a high-strength boron fiber plus soft aluminum matrix showed that in the first approximation it is sufficient to consider the first term in expansion (3). Then the equation for the ascending branch of the mechanical hysteresis loop considering the modulus of deformation hardening of the matrix $D_M\Pi$ will be described by the parabolic curve:

$$\sigma = (E_B \nu_B + E_M \nu_M)\varepsilon - \frac{E_B E_M (1 - D_{M\Pi}/E_M)}{2M} \varepsilon^2 \; . \tag{4}$$

Here M is a structurally sensitive parameter with a clear physical sense, equal to the effective stress on the high-strength fibers at which the entire volume of the "soft" matrix is plastically deformed. The value of M can serve as an additional characteristic of a fiber composite material to estimate the intensity of development of inelastic deformations under load.

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UDC 539.4:620.178.3

FATIGUE FRACTURE OF GAS TURBINE COMPRESSOR BLADES OSCILLATING IN VARIOUS NATURAL FORMS

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The blades of aviation gas turbine engine compressors are the most heavily vibration-stressed parts of these machines. When blades are manufactured of fiber composites, the problem of assuring vibration resistance is no less pressing than it is for ordinary metal blades. The difficulty of assuring vibration resistance of composite blades is great, since the reinforcement structure is variable over the length of the blade and the reinforcement orientation varies with respect to the direction of the cyclical stresses. Also, composite blades with both polymer and metal matrices have low erosion resistance, making the use of composites more difficult. It is impossible to use composites in turbine blades without solving the problem of protection from erosive wear.

This report discusses the behavior and fatigue fracture of glass-reinforced plastic blades and blade models (plates) with metal and polymer protective erosion-resistant coatings applied to the surface. The following types of coatings were studied: nickel, aluminum, brass screen, whiskerized paper and VK-3.

It was found that in composite blades there is no single type of fracture (as in metal blades) which dominates. In uncoated blades we observed delamination and in places a transition from the blade to the root, breakage of fibers, separation of entry and exit edges and at the joint, cracking of the matrix, splitting in areas with predominantly unidirectional reinforcement. With some forms of oscillation cracks appeared in surprising locations and directions. The picture is still more complex in models with coatings.

With nickel coating, fracture occurs in the form of major cracks in the coating at points of maximum deformation, delamination and failure of the coating or simple delamination of the coating without failure. Delamination at the edge of the plate was observed. The aluminum coatings delaminated and fractured, the base material remaining whole. Application of a brass screen to the surface of the plates resulted in separation of the base material near the neutral line. Testing of plates with VK-3 phenol-rubber coating revealed initial swelling and carbonization of the coating. This form of failure — thermal failure — is seen in a number of cases of high-frequency testing of materials under conditions which hinder heat transfer. Vibration and heating become more significant as fatigue damage accumulates. Based on an analysis of the changes in resonant frequency and temperature of the object tested with the number of cycles, a new method is suggested for fatigue testing of composite materials. The accumulation of fatigue damage upon oscillation is described by the change in resonant frequency, deformation capacity and temperature of the object over time.

The natural oscillating frequency of blades and plates is more sensitive to changes occurring in the material during cyclical loading than the damping capacity, estimated from the width of the resonant curve.

We should note that the application of even a thin protective layer to the surface of a plate influences its elastic properties, frequency spectrum and vibration strength, represented by its resistance to fatigue and its damping capacity.

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INFLUENCE OF INTERMEDIATE LAYER BETWEEN FIBER AND MATRIX ON THERMAL FATIGUE DURABILITY AND LONG-TERM STRENGTH OF COMPOSITES

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In developing heat-resistant composites, it is usually impossible to combine high heat resistance and thermal fatigue durability of the composite under cyclical temperature change conditions. A composite with continuous, unidirectional fibers, due to the specifics of distribution of the spatial stress field, has maximum thermal fatigue damage of the material in the volume of the matrix, located near the boundary with the fiber [1]. Therefore, changes in the properties of the volume of the matrix due to processing (e.g., alloying) or introduction of a thin layer at the fiber boundary may significantly change the thermal fatigue strength of the composite. In this connection, we studied the influence of the mechanical properties of the intermediate layer on the heat resistance and durability of a composite.

Studies were performed by numerical methods on a solid model of a heat-resistant composite consisting of a matrix alloy of moderate heat resistance, EI 765, reinforced with tungsten fibers. During the computations, we considered the elastic-plastic deformation and creep deformation, as well as the variation of mechanical properties of the composite components as functions of termperature. Type Kh18N10T stainless steel was used as the intermediate layer, plus 1Kh11V2MF steel, which is used in power engineering. These steels have higher relaxation properties and resistance to thermal fatigue than the matrix material. Therefore, their use in the composite decreases the amplitudes of deformations in the matrix and the fibers due to changes in temperature, which increases the thermal fatigue durability of the composite. However, they decrease the long-term strength of the composite. Considering this, the purpose of this work was to study the possibility of significantly increasing the thermal fatige durability of the composite without significantly decreasing its long-term strength.

Thermal cycling was performed mostly as follows: maximum temperature 850 ° C, minimum temperature 20 ° C, heating and cooling rate 5 ° C, holding at maximum temperature 1800 s, minimum external tensile stress applied to matrix 300 MPa. Depending on the volumetric fraction of fibers, a study was made of the influence of intermediate layer thickness on the following properties of the composite: deformation hardening in second stage of deformation, long term (100 hr) strength, total accumulated deformation, number of thermal cycles to development of a macrocrack in the matrix. It was found that with decreasing thickness of the layer, there is a sharp and nonlinear increase in long-term strength of the composite and much less decrease in thermal fatigue durability. This results from the change in the spatial stress field in the intermediate layer and in increase in the constricted nature of deformation with a decrease in thickness. As a result, it becomes possible, with proper selection of the material of the layer, to increase the thermal fatigue durability of a composite without significantly decreasing its long-term strength. Since the gradient of change in damage to the material in the radial direction increases with a decrease in the volumetric fraction of fiber, this effect is stronger with volumetric fractions of less than 0.35-0.4. This effect also appears primarily in modes of loading with great external stress with comparatively short holding in the area of maximum temperature. Consequently, we can conclude that the inclusion of an intermediate layer in a composite allows more flexible regulation of its mechanical properties under cyclical temperature change conditions.

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UDC 669.494

OPTIMIZATION OF FIBER COMPOSITE MATERIAL STRUCTURE

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The most important structural characteristics, significantly influencing the physical-mechanical properties of fiber composite materials, are the volumetric fraction of fiber Vf and the density of seizing foci at the interface between the components θ. Whereas the former characteristic is purely geometric and independent of the technology used to manufacture the fiber composite material, the latter is determined by physical and chemical processes occurring at the interface between the components and is determined by the manufacturing technology. Published theoretical and experimental data indicate that optimization of the values of these structural characteristics in terms of a single property — longitudinal tensile strength σc — is a difficult problem. Obviously, the problem is still more complicated if we attempt to optimize the structure of the fiber composite material for several properties, such as for σc and shear strength τc. Solving this sort of multiple-criterion, multiple-parameterproblem demands a tool convenient for practice. Such a tool might be a diagram of the isolines of properties of the fiber composite material. The essence of the idea we are suggesting is that lines be drawn in the coordinate system Vf-θ, representingthe constancy of the numerical value (isoline) of some physical-mechanical property of the material. Let us clarify the role of the isoline diagrams in the optimization of composite material structure by analyzing a few examples. Figure 1 shows the isolines of a boroaluminum-class composite with high-strength fiber and a low-strength matrix. This figure demonstrates that in terms of some criterion, e.g., "$\sigma s \geq 1400$ MPa" the optimal area of values of Vf and θ is that located to the right of the 1400 MPa isoline (Figure 2a). We also see that a longitudinal strength of 1400 MPa cannot be obtained at any value of θ if Vf 0.575 (Figure 1). If the optimization criterion is "$\sigma s \geq 1200$ MPa," as we can see from Figure 2b, there are two areas of values of Vf and θ, merging in the lower portion of the figure, which are optimal. Figure 3 shows a diagram of the isolines of τc for the same class of materials. Analyzing this figure, we see that, e.g., in terms of the criterion "$\tau c \geq 0.8\ \tau m$" (where τm is the shear strength of the matrix), the optimal area of values of Vf and θ is that located above the0.8 isoline. The structure of the material can be optimized for both of these criteria by simply combining the isolines for σc and τc on a single diagram. Figure 4 illustrates this case. It follows from it that in order to meet both requirements "$\sigma c \geq 1200$ MPa, while $\tau c \geq 0.8\ \tau m$" the values of Vf and θ must be located in the area which is shaded in Figure 4. Thus, optimization of the structure of a fiber composite material with respect to two criteria, as would be expected, decreases the area of optimal values of the structural parameters. Obviously, isoline pictures?? can be used to optimize the structure with respect to other criteria related to the physical and mechanical properties of the material. For example, we might assume that the damping properties of the fiber composite material are improved by decreasing both the density of seizing of foci and the volumetric fraction of fibers. In this case, the isoline of the parameter representing this material property should be drawn as is shown in Figure 4 by the dash line. If we require that damping properties of the fiber composite material be no worse than some

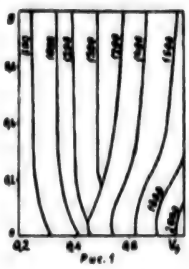

Figure 1

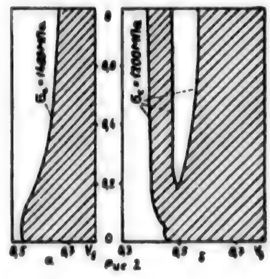

Figure 2

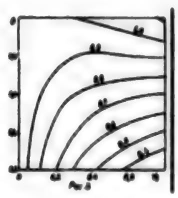

Figure 3

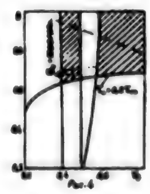

Figure 4

certain value, this isoline will provide another limitation, but at the top, of the area of optimal values of the structural parameters.

We must note in conclusion that the isoline pictures can be used to optimize the structure of a fiber composite material not only with respect to a set of physical-mechanical properties, but also with respect to economic and other criteria, if the relationships between these properties and structural parameters are known.

Conclusions

1. Pictures of the isolines of various physical and mechanical properties of a fiber composite material represent a convenient tool for optimization of the structure, as represented by the volumetric fraction of fiber and the density of seizing foci.

2. Isoline pictures can be used for multiple-criterion optimization of the structure of a fiber composite material. Areas of optimal values of the structural parameters can be delineated, corresponding to the requirements for each optimization criterion.

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CONCEPTS OF PHYSICAL-MECHANICAL MODELS OF THREE-DIMENSIONALLY REINFORCED COMPOSITE MATERIAL

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Three-dimensionally reinforced composite materials based on a brittle matrix are suitable for specific usage conditions and have natural heterogeneity. Therefore, it is important to determine the specifics of the behavior of these materials and structures made of them.

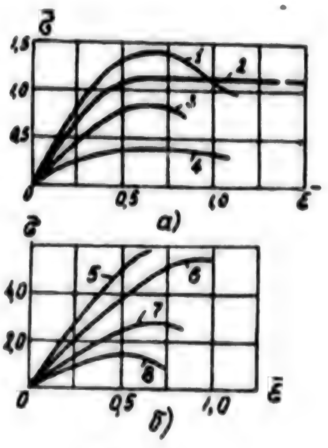

Figure 1

In this work, an experimental and theoretical study was performed of the deformation of such materials with three-dimensionally orthogonal equilibrium linear structure using a brittle gas-phase matrix. A series of tests was performed under static tensile and compressive loading in the directions (*X, Y, Z*) and at angles of 30° and 45° in the reinforcement planes. Figure 1 shows sample diagrams of deformation in the coordinates

$$\bar{\sigma} \sim \bar{\varepsilon} \; (\bar{\sigma} = \sigma/\sigma_*, \; \bar{\varepsilon} = \varepsilon/\varepsilon_*).$$

Curves 1, 2, 3 and 4 in Figure 1,a were obtained in extension in the directions X, Z, 45XY, 45 XZ, while curves 5, 6, 7 and 8 in Figure 1,b were obtained in compression in the directions X, Z, 45XY, 45XZ. These graphs show the significant nonlinearity not only in the direction of disorientation, but also in the directions of reinforcement. This is characteristic of the behavior of this material. The nonlinearity is physical-geometric in nature, due to the peculiarities of the structure and its operation. In some cases, the curve in the initial stage of deformation showed reverse convexity, also related to the specifics of operation of the material.

The spectrum of mechanical properties of these composite materials is illustrated by Figure 2 (Figure 2,a shows the strength characteristics, Figure 2,b — the elastic properties, Figure 2,c — the pseudoplasticity). The anisotropy results from the properties of the components of the composite and the various fracture mechanisms, as determined by microstructural and fractographic studies. We know that these composites have significant microscopic and macroscopic porosity. According to the physical experiments, the macroscopic porosity represents 30-35% of the volume,

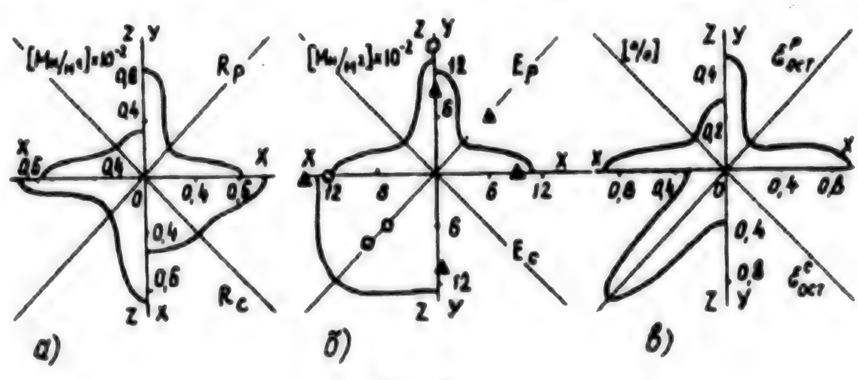

Рис.2

Figure 2

the microscopic porosity — 10-20%. However, excursions are possible, in which the cells of the structure are not 100% filled by the matrix. Thus, the matrix material groups the filaments of the reinforcing filler into random bundles and coats the peripheral area of the cells. This results in an increase in the anisotropy gradient of the material, causing the strength properties to become unstable.

A mathematical description of the physical and mechanical properties of three dimensionally reinforced composite materials is difficult in principle, a result of the complexity of the mechanism of deformation and fracture. There are as yet no sufficiently reliable mathematical models to describe the properties of these materials. Among the best known are the method of mixtures (as in [1]), the energy method of Johnson[2] and the structural approach of Delneste[3].

The basis of the models of three-dimensionally reinforced composites is the hypothesis of their reduction to a plane orthogonal or one-dimensional reinforcement. The transition to a three-dimensional system is made by averaging the components of the physical equations based on the condition of Voigt and (or) Rice[1].

$$<\sigma_{ij}> = B_{ij} <\varepsilon_j> \quad \text{per Voigt} \qquad (1)$$

$$<\varepsilon_{ij}> = A_{ij} <\sigma_j> \quad \text{per Rice} \qquad (2)$$

$$i, j = 1, \text{-}6.$$

Here B_{ij}, a_{ij} are the rigidity and compliance matrices of the composite considering fluctuation components. The brackets in (1) and (2) represent averaging.

Calculation of the elastic components of the material, considering and ignoring porosity, disagree within limits of 0.84-4.15 ($E_{ij}/E_{ij}ex$ = 0.84-1.27, i = j; $E_{ij}/E_{ij}ex$ = 1.41-2.22, i ≠ j — considering porosity; $E_{ij}/E_{ij}ex$ = 1.22-1.39, i = j; $E_{ij}/E_{ij}ex$ = 4.05-4.15, i ≠ j — ignoring porosity). In Figure 2 the calculated points are marked with a black triangle and a circle, respectively.

Method 2 basically utilizes the experimental curves which are processed according to the equation

$$E_{ij} = A_i\left[1 - B_i\left(\frac{U_{ij}}{U_0}\right)^{C_i}\right]; \quad i, j = \overline{1, 6}, \qquad (3)$$

where A_i, B_i and C_i are experimental constants;

U_{ij}, U_0 are the deformation energies calculated from the diagrams.

Calculations performed with equation (3) showed less disagreement (E_{cal}/E_{ex} = 0.27-1.02; G_{cal}/G_{ex} = 0.5-0.95).

However, these models do not consider a number of peculiarities of the structure of three dimensionally reinforced composites (at the microscopic and macroscopic levels). In this respect, the structural method is preferable[3].

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UDC 539.3

ANALYSIS OF ELASTIC-PLASTIC DEFORMATION OF MULTILAYER METAL COMPOSITES CONSIDERING STRUCTURAL BREAKDOWNS

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Attempts to make more complete use of the load-bearing capacity of important structures require analysis of inelastic deformation of composite materials, resulting not only from physical nonlinearity, but also from the failure of individual structural elements.

The authors have developed mathematical models of deformation and failure of structurally heterogeneous materials by the use of microscopic and macroscopic damage tensors[1], the theory of plasticity of anisotropic media of B. Ye. Poberdi and a combination of strength criteria. The stochastic boundary-value problem of elastic-plastic deformation (loading) of multilayer composites in an arbitrary, macroscopically homogeneous stress-strain state, is stated and solved. A new probabilistic approach is suggested to modelling of stochastic processes of structural breakdown. It is assumed that the macroscopic volume of composite material studied, since it is represented at a fixed level of macroscopic stresses (or strains), contains elements of the structure which fail according to all probable mechanisms, while their volumetric fraction can be computed from the probabilities of microscopic failure.

Results of numerical computer modelling of the processes of deformation and failure of an aluminum-magnesium composite are obtained. All effective material functions are computed for this composite. The residual stress and strain arising when the load is relieved are studied (Figure 1). The specific features of deformation are analyzed: plastic compressibility, the disagreement between simple deformation processes at the macroscopic level and simple deformation processes of structural elements.

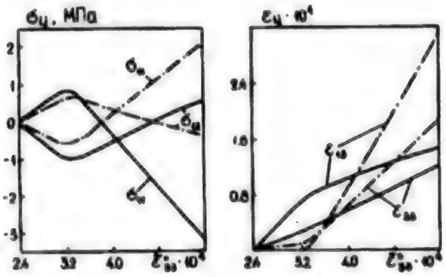

Figure 1

Residual Structural Stresses and Strains

$\overrightarrow{\varepsilon_{33}}$ is the level of macrodeformation achieved by the moment of unloading ($\overrightarrow{\varepsilon_{33}} = \overrightarrow{\varepsilon_{13}} = 2\overrightarrow{\varepsilon_{12}}$), the solid lines are the aluminum layers, the dot-dash lines are the magnesium layers. The x_3 axis is perpendicular to the plane of the layers

Equilibrium deformation diagrams are obtained for the developing process of structural failure (Figure 2), explaining and illustrating the damping effects (the "tooth" and "steps" on the diagram, the descending limb) for various structurally heterogeneous materials. The effect of local relief caused by failure of structural elements is discovered and investigated (cf. Figure 2). The solid lines in coordinates $\overline{j}_\varepsilon^{(2)}$ and $\overline{j}_\sigma^{(2)}$ (invariants of structural deformation and stress tensors2) show the behavior of undamaged aluminum layers, while the dot-dash lines show the behavior of magnesium layers, $j_\sigma^{(\cdot)}$ and $j_\varepsilon^{(\cdot)}$show the invariants of macrostress tensor σ^* and macrostrain tensor ε^* [2]. Points with identical number correspond to one level of macroscopic deformation

$$(2\varepsilon_{11}^* = 2\varepsilon_{22}^* = \varepsilon_{33}^* = 2\varepsilon_{12}^* = \sqrt{2}\varepsilon_{13}^* = \sqrt{2}\varepsilon_{23}^* \neq 0).)$$

The highest points on the diagrams correspond to the maximum possible values of stress which can be achieved for a material under these conditions, for which structural failure begins to occur in avalanche fashion. The descending branch shows that the applied load must be reduced to stabilize this process.

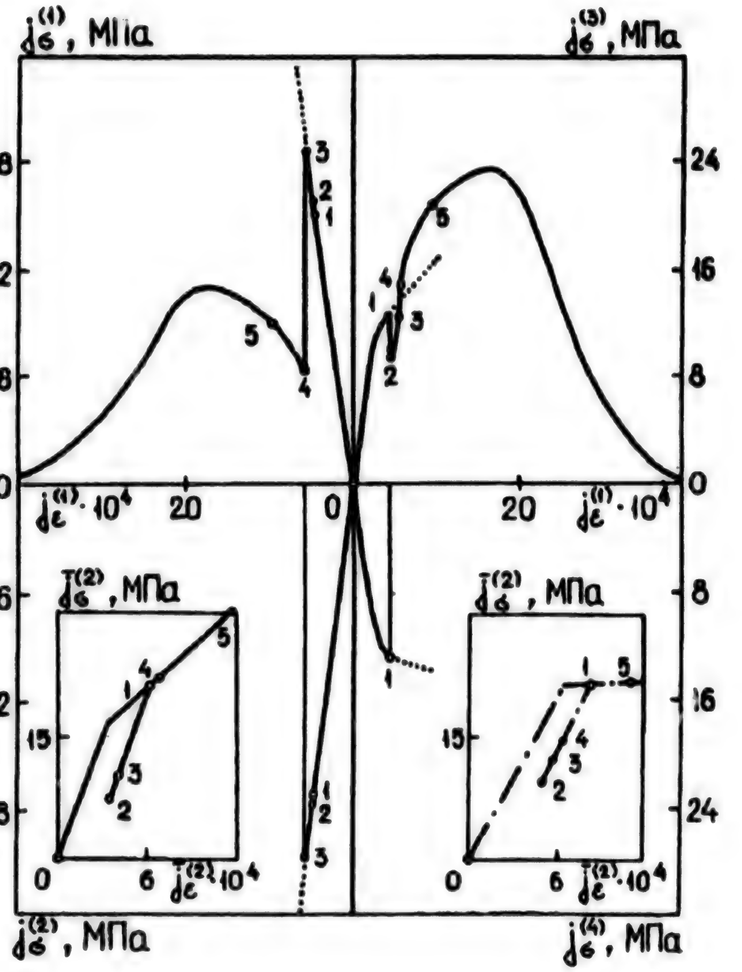

Figure 2
Local Load upon Deformation of Composite

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UDC 539.3

ELASTIC-PLASTIC DEFORMATION OF UNIDIRECTIONAL TITANIUM-BASED METAL COMPOSITES

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Models of microheterogeneous media with periodic placement of inclusions in the matrix are widely used in the study of structural and macroscopic deformation of unidirectional reinforced composites. The solution of the linear and nonlinear problems of micromechanics by the use of such models allows, on the one hand, investigation of the specifics of the mechanical behavior of the matrix and the fibers before structural failure and, on the other hand, prediction of the effective thermoelastic and elastic-plastic properties of the composites as functions of the morphology and properties of the components.

This work presents the results of numerical solution of elastic-plastic problems involving arbitrary loading in the transverse plane of unidirectional composites with VT-1-0 titanium alloy matrix and boron and molybdenum fibers. The tensile curve for the matrix was approximated by a three-part broken line with subsequent analytic construction of the material function from the deformation theory of plasticity suggested by A. A. Ilyushin for an isotropic matrix with complex stress state. After the boundary-value problem was solved for a periodicity element by means of the averaged deformation fields using well-known precise expressions from micromechanics, the effective longitudinal and transverse Young's modulus and shear modulus of the metal composites were computed, as well as Poisson's ratio and the coefficient of thermal expansion for the longitudinal and transverse directions. The development of microplastic zones in the matrix and their influence on macroscopic properties are illustrated. Examples are presented of the computation of effective material functions from the anisotropic theory of plasticity of metal composites, allowing prediction of the mechanical behavior of structures experiencing elastic-plastic deformation. A new physical-mechanical effect is discovered: with a fixed, simple process of deformation of a composite as a whole, at various points in the metal matrix processes with complex trajectories can occur.

It was demonstrated (Figure 1) that reinforcement of titanium with fibers having different mechanical properties (boron, molybdenum) produces different types of elastic-plastic deformation of the matrix. Thus in titanium-molybdenum composites, the generation and development of microplastic zones starts at the phase interface, while in titanium-boron composites it starts at some distance from the interface. In the first case the generation and development of microplastic zones is discrete in the initial stage. However, structural failure of the matrix (exhaustion of the plasticity) in both cases arises near the phase interface, corresponding to the experimental data published in fractographic studies. Computer modeling of composite deformation processes allows the level of development of plastic zones in the matrix to be estimated (Figure 1, Figure 2 for titanium-boron composite), for which the deformation of the entire composite is still quasielastic. The relative change in longitudinal E^*_k and transverse $E^*_\perp$ Young's modulus, as well as Poisson's ratio, representing constriction in the transverse plane upon extension in the same plane ($\nu^*_{\perp\perp}$) and in the direction of reinforcement ($\nu^*_{\perp k}$) are shown in Figure 2. Figure 3 shows that at various points in the matrix deformation processes occur which are different from the simple processes and have different degrees of curvature, whereas the macrodeformations vary according to the simple rule $\varepsilon_{*ij} = \beta e_{ij}$ (where e_{ij} is the arbitrarily fixed Cauchy deformation tensor for shear deformation, β is a parameter of the process). The effect which is discovered must be considered in structural analysis of inelastic deformation of metal fiber composites and structures made of these composites in the selection of the equations for elements of the structure. These equations must be valid for processes of small and moderate curvature even in cases where the loading on the entire structure is simple to assure adequate modeling of the real microscopic stress and strain fields, thus assuring reliable computation of the effective properties of elastic-plastic composites. In this sense, solutions using the deformation theory of plasticity must be considered a first approximation, to be further refined by experimental data.

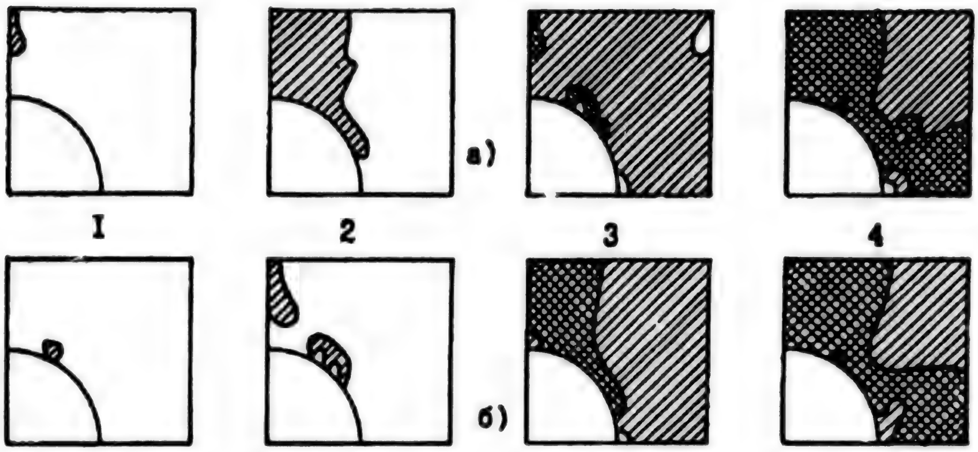
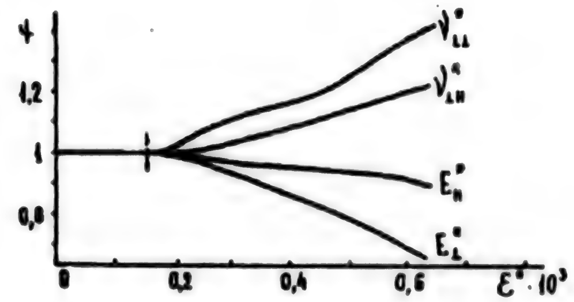


Figure 1
Development of Plasticity in Matrix of Titanium-Boron (a) and Titanium-Molybdenum (b) Composites



Effective elastic constants:
$E^*_{||} = 200GPa$, $E^*_{i} = 160.1\ GPa$
$\nu^*_{ii} = 0.376$, $\nu^*_{i||} = 0.303$

Figure 2
Change in Mechanical Properties of Titanium-Boron Composite

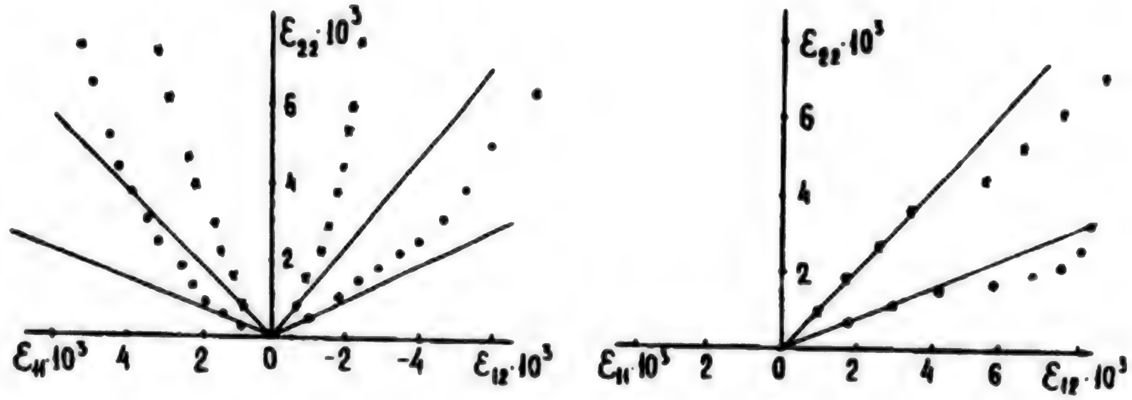


Figure 3
Deformation Trajectory at Characteristic Points of Elastic-Plastic Matrix in Ti-Mo Composite

UDC 539.37

CREEP OF BIMETALS AT ELEVATED TEMPERATURES

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This article studies the behavior of bimetallic materials under creep conditions at elevated temperatures.

A flat specimen is analyzed, consisting of two metal strips welded together having different physical-mechanical properties. The specimen is exposed to tensile stress at constant temperature. Since the two metals have different coefficients of linear expansion upon heating, the temperature stresses may be different not only in magnitude, but also in sign. It is important that the stress function at individual points may have a discontinuity, while the strain function must be continuous due to the bonding between the individual strips.

In calculating small creep deformations, it is possible to ignore the curvature of a specimen and consider that all layers of the bimetallic strip undergo identical creep deformation.

The initial equation is the equation of equilibrium of internal forces acting in an arbitrary transverse cross section of the bimetallic strip, written in the following form:

$$\int \sigma i(y,t) b dy = p,$$

where: $\sigma i(y,t)$ is the normal stress at the point with coordinate y at arbitrary moment t for bimetal i, i = 1, 2; b is the width of the strip; p is the tensile stress.

Using the assumption of equal creep deformation of different layers within a strip, we can express $\sigma_i(y,t)$ as $f(\sigma i(0,t);y)$. Solution of the equation presented above yields $\sigma i(0,t)$.

In computing the creep of a bimetallic strip, the stress-strain state of the metals of the individual layers is described by the equation of state of reonomic bodies.

The use of this model with constant characteristics (Burger's bodies) yields a clear interpretation of the mechanics of the creep process. A Burger's body is convenient for the description not only of the qualitative, but also of the quantitative aspect of the rheologic phenomena. In the model used, creep deformation is divided into reversible and irreversible components. This allows description of anomalies consisting in that after the external load is relieved only a portion of the deformation which was accumulated during the unsteady creep stage disappears. The mathematical apparatus of the equations of state of this model allows us to compose and relatively simply solve a nonlinear equation for the equilibrium of internal forces in the cross section of the bimetallic strip. This equation also reflects the process of simultaneous development of creep and stress relaxation, a peculiarity of the stress-strain state of the bimetal when the deformation of the two metals at their interface must be identical.

Thus, for a bimetallic strip the creep deformation is

$$\varepsilon_n = \sigma_1(0;t)\left[\frac{1-e^{-\frac{E_{11}}{\eta_{11}}t}}{E_{11}} + \frac{t}{\eta_{21}} + \frac{1}{E_{21}}\right] - \varepsilon_{31}(0;0),$$

where E_{11} and E_{21} are the elastic characteristics, η_{11} and $\eta 21$ are the viscous characteristics of the Burger's body, found from experimental data by means of the creep curves of homogeneous materials; $\varepsilon 31$ (0;0) is the instantaneous deformation at t = 0 for a point in the first layer with coordinate y = 0, found by calculating the instantaneous stress-strain state.

The results obtained can be used for calculations of the rigidity and strength of structures of bimetallic strips with long-acting loads under elevated temperature conditions.

UDC 539.3:620.1

ESTIMATE OF MECHANICAL PROPERTIES OF MULTILAYER MATERIALS

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Reliable determination of the properties of composite materials is an important problem due to the successes which have been achieved in their manufacture and their increasingly widespread use in industry. Experimental estimation of properties requires that we solve the question of the geometry and dimensions of specimens in connection with the heterogeneous structure of the material and the need to include all structural elements of the composition in the cross section of the specimen.

This work defines the mechanical properties in static extension of flat specimens and the cyclical crack-formation resistance in three-point flexure of prism-shaped specimens with preliminary cracks. The composite material was made up of sheets of the alloys VT23 and PT3V. The change in properties of a multilayer composite with the thickness of the layers, width of specimens and relative content of plastic component was studied.

As the thickness of the sheets was increased from 0.5 to 2.0 mm, no change was determined in the strength characteristics of the multilayer composite, though there was a tendency toward reduced plasticity. The properties were more influenced by specimen width. Thus, increasing specimen width by 1.6 times caused a decrease in relative elongation of 30%. As the relative fraction of the less strong and more plastic alloy PT3V was increased, a systematic change in the strength characteristics was observed in the direction of higher values than that indicated by simple additive calculation.

The influence of the structure of the composite (mutual location and relative thickness of layers) on crack growth resistance was studied. The crack growth rate in the layers agreed with the initial properties of the materials of the layers. As the thickness of the plastic layer decreased, its inhibiting effect was reduced. Delamination, the most effective method of stopping cracks, occurred at the layer interface.

UDC 539.378

THEORY OF SMALL ELASTIC-PLASTIC DEFORMATIONS OF CHAOTICALLY REINFORCED COMPOSITE MATERIALS

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This report presents studies of the elastic-plastic behavior of composite materials consisting of several different components. The stress-strain and functions describing the mechanical properties of the composite are assumed to be statistically homogeneous, ergodic random fields. Statistical averaging of the system of equilibrium equations of the composite material can be used to establish its macroscopic defining equations to compute the effective characteristics. The behavior of the composites is studied with various degrees of bonding of the components. Cases are studied in which one of the components acts as a binding matrix, while the others form separate inclusions, as well as cases in which the matrix consists of several mutually penetrating components. A study is made of the influence of the shape of ellipsoidal inclusions on the effective properties of chaotically reinforced composites. The limiting cases are models of porous media and composites containing rigid inclusions which are not deformed. It is noted that in spite of the initial plastic incompressibility of the materials of the components, the composite as a whole does have some plastic compressibility, resulting from the difference in the elasticity moduli of the components.

Numerical analysis of the results obtained shows satisfactory agreement with experimental data.

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UDC 539.3

EFFECTIVE ELASTIC AND CONDUCTIVITY CHARACTERISTICS OF MAGNETOELASTICITY IN LAYERED AND UNIDIRECTIONAL FIBER COMPOSITES

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The possibility of predicting the physical-mechanical properties of composite materials based on the known properties of their components, their concentration and spatial distribution, requires the development of analytic methods for the solution of this problem.

This work, based on the method of averaging differential equations with partial derivatives with rapidly oscillating coefficients[1,2], presents a calculation of the effective material parameters — elasticity moduli and conductivity coefficients for the following periodic materials:

1. A multilayer composite;

2. A fiber composite with unidirectional reinforcement.

A "zero approximation theory" is developed, which can be used, by solving the problem only based on the theory of the effective modulus, to find the approximate microscopic displacement, microscopic stress and electromagnetic field at the microscopic level.

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UDC 620.178.311

STUDY OF MECHANICAL BEHAVIOR OF METAL RUBBER ANALOGUE UNDER COMPRESSIVE AND SHEAR DEFORMATION BY PHYSICAL MODELING

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The material MR (metal rubber analogue) is a metal composite material obtained by cold pressing of spiral wire segments placed in the press mold so that they overlap.

There are methods to design certain structures of MR, based on summarizing the experience of producing specific products and experimental studies of their elastic-friction characteristics. This approach has limited capability for the development of new and improved structures and does not allow prediction of changes in their elastic-physical characteristics as such products are used.

There are also methods to design products from MR which do not have these limitations. They are based on physical modeling of the individual elements of the material (turns of the spirals) and the processes occurring in them. However, the physical models known at present cannot be implemented; furthermore, they only allow investigation of the mechanical behavior of MR specimens in compression. Under real conditions, MR products are most frequently loaded in both compression and shear. Therefore, the creation of a usable physical model reproducing the processes of interaction of MR elements in compression and shear is of both scientific and practical significance.

The model here suggested is a set of pairs of pyramid-shaped elements (Figure 1) turned tip to tip toward each other and interacting with each other along the lateral surfaces.

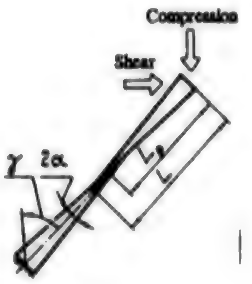

Figure 1

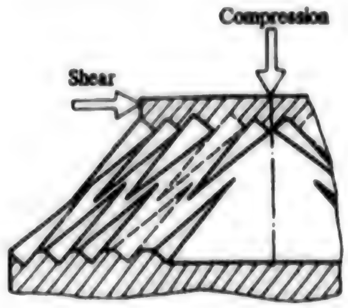

Figure 2

Within the volume of the model the pairs of pyramids are concentrated in equilibrium-force groups (Figure 2) distributed in layers, with the gap between the pyramids of each subsequent pair within the same layer differing by a constant quantity which is equal to the deformation step.

The pyramids are sloped relative to the vertical axis by angle γ, which is equal to the mean angle of orientation of the spiral turns in the material.

During deformation the number of contact points between the pyramids in a pair increases in proportion to the deformation. The greatest number of pyramid pairs is determined by the number of contacts of spiral turns within the volume of a real MR specimen deformed to the maximum permissible deformation.

The external load is applied to the first layer of the model and is transmitted during deformation through the contacting pairs to the other layers.

The processes of cyclical deformation of the model are described by complex equations obtained by methods of the strength of materials.

The process of loading

$$P_n = \chi(\alpha, \gamma, L, f, E) \sum_{i=1}^{n} \frac{i}{n} \frac{1 - \zeta_{p_i}}{\zeta_{p_i}^3} y_n ,$$

where α, γ, L, $\bar{L}_{pi}$ are the geometric parameters of the model (cf. Figure 1); f is the coefficient of friction between the pyramids of the pairs; E is the modulus of elasticity of the material of the pyramids; k is the number of pyramid pairs in contact when the model is deformed by y_H; $\bar{L}_{pi} = L_{pi}/L$ is the relative coordinate of the center of the contact area of pyramid pair i (cf. Figure 1).

The process of unloading

$$P_p = F\left[y_p\left(y_{p1i}\,;\,y_{p2i}\right)\right],$$

where

$$y_{p1i} = y_{ci}\,\lambda(\alpha, \gamma, L, \bar{L}_{pi}, f, E)$$

is the deformation of the model from the start of the process of load relief up to separation of pyramid pair i;

y_{ci} is the deformation of pyramid pair I from the moment of separation to the moment of delamination;

$y_{p2i} = \Delta y m_0$ is the deformation of the model from the start of load relief until delamination of pyramid pair i;

Δy is the deformation step of the model;

m_0 is the number of delaminated pyramid pairs.

Analysis of the hysteresis loops of the natural and model specimens confirms the adequacy of the model of MR in terms of its elastic-friction characteristics under compressive (Figure 3) and shear (Figure 4) deformation.

The disagreement (up to 20%) between experimental and model hysteresis loops results from averaging of the coefficient of friction throughout the entire area of deformation of the MR. In reality, the coefficient of friction is not constant but rather changes as a function of the contact area of the spiral turns and the compressive load between them.

Solution of the problem of deformation of the model can be used to determine the compressive loads between elements and establish a program for their interaction in the process of cyclical and arbitrary loading in compression and shear.

The results obtained allow us to explain a number of qualitative and quantitative regularities of the behavior of MR as it is deformed and to expand our concept of the physical and friction processes occurring at the contact points between individual elements.

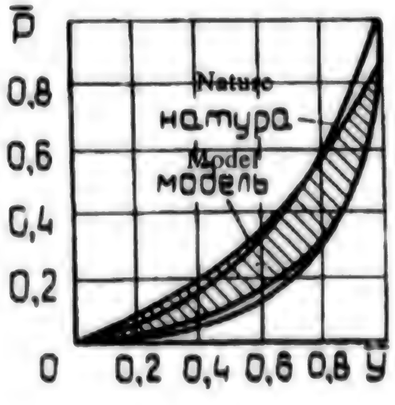

Figure 3

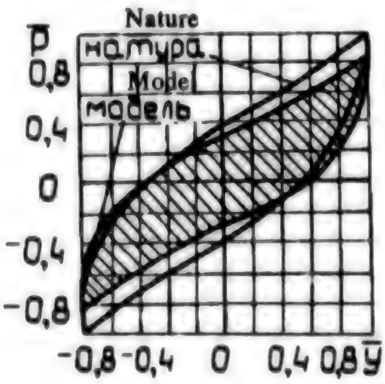

Figure 4

620.178.311

DESIGN OF A VIBRATION-PROTECTION SYSTEM WITH SIX DEGREES OF FREEDOM USING MR VIBRATION ISOLATORS

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Type DKU vibration isolators made of the metal composite material MR, obtained by cold pressing of chaotically placed wire spirals reinforced with high-strength wire cord, have been widely used in modern technology due to their good damping and strength properties. The elastic-damping characteristics of these vibration isolators are essentially nonlinear, making it difficult to create methods for optimal design of vibration-protection systems. One of the main problems arising in the design of such systems is determination of the resonant frequencies. Attempts to use the linear theory for this purpose result in errors of up to 70%. Therefore, the design of vibration-protection systems with type DKU vibration isolators is a pressing problem.

The dynamic characteristics of vibration-protective systems with many degrees of freedom are frequently computed by means of a simplifying nonlinear-oscillator model. The differential equation for the oscillations is solved by the method of harmonic linearization, in which the nonlinearity of the elastic-damping characteristics of the vibration isolator is considered by the variation of rigidity $C = C(A)$ and absorption factor $\psi = \psi(A)$ as functions of deformation amplitude A. The error of this method for type DKU vibration isolators is not over 2-5%.

This method can be extended to systems with several degrees of freedom if we can find the characteristics $C_i = C_i(A_i)$ and $\psi_i = \psi_i(A_i)(i = 1, 2, ..., n;$ n is the number of degrees of freedom), where $(c_i/Aj) = 0$, $(\psi i/A_j) = 0$ where $i \neq j$. However, nonlinear systems do not have this property, since the principle of superimposition is not valid in them. Therefore, one measure of applicability of the harmonic linearization method is the extent of deviation from the principle of superimposition.

In order to determine the deviation from the principle of superimposition of elastic-damping characteristics of type DKU vibration isolators, an experiment was performed involving loading of a vibration isolator at angle α element [0; 90] to the axis of the vibration isolator. The experimental reaction was compared with the value of the reaction calculated by the principle of superimposition using rigidity in the axial and radial directions. The disagreement was 2-10% which, in our opinion, is sufficient for design purposes using the method of harmonic linearization.

Let us now study the design of vibration isolating systems with six degrees of freedom. Since the resonant frequencies of the system are close to the natural frequencies of the system without damping, we will analyze the free oscillations of the system[1]. Let us also assume that the amplitude of oscillations A_k in the direction of coordinate k depends only on the amplitude of excitation ak and damping ψk in the same direction. This allows us to estimate the amplitude. For example, for kinematic excitation with constant acceleration $Ak = 2\pi\alpha_k/\psi_k$. In the operating range of amplitudes, the characteristics $C = C(A)$ and $\psi = \psi(A)$ are rather smooth (a change in A by 10% results in a change in C and ψ by 2-4%) and therefore inaccuracy of the estimate cannot result in significant error.

The rigidities in the directions of the main coordinate axes included in the equations presented in 1 depend on the amplitudes of deformation of the vibration isolators: $Cx = Cx(A_x)$, $C_y = C_y(A_y)$, $C_z = C_z(A_z)$. Estimation of the deformation amplitudes requires the equation $\psi x = \psi\Phi x(A_\xi)$, $\psi_y = \psi_y(A_y)$, $\psi_z = \psi z(A_z)$.

The value of a_k depends on the oscillating frequency ωk in direction k, which is not known to us. Ak depends on ψk which, in turn, depends on Ak. An iterative process is used to balance these quantities.

By fixing the values of ωk, we can obtained ak and estimate Ak. The equations presented in 1 define the influence factors, allowing us to find the amplitudes of the coupled oscillations. Using these amplitudes and the coordinates of the vibration isolators, we can find the deformation amplitudes of each vibration isolator in the direction of the three main axes and determine the summary values cx, cy, cz and the mean values ψx, ψy, ψ_ζ. Substituting the rigidities into the equations, we then find the refined value of ω_k and repeat the process until the desired accuracy is reached.

This method was used to develop a program to compute the resonant frequencies and resonant ampli-

tudes of a vibration-isolating system with 6% of freedom. The program can be used to perform calculations in dialogue mode with various positions of the points of attachment of the vibration isolators and for various types and sizes of isolators. This allows optimization of the characteristics of the system. As a result of the calculation, we can find the load on each vibration isolator and its required elastic-friction characteristics, allowing us to perform a test calculation with a single-mass scheme and optimize the characteristics of the vibration isolators2.

In order to check the method, it was used to calculate the resonant frequencies and amplitudes of a vibration-damping system with 2% of freedom (translational and rotational oscillations in one plane), and the results were compared with the results of a program which performs numerical solution of the differential equations for the oscillations using the mathematical deformation model of 3. The disagreement was 11%.

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539.3:620.1

MODEL OF FAILURE OF HIGHLY POROUS MATERIALS WITH RESTRICTED LATERAL DEFORMATION

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Modern techniques allow us to produce metal-air composites with up to 85-90% porosity. One possible method is chemical or mechanical precipitation of metals on a polyurethane foam base with subsequent heating to the ignition point of the base and high-temperature sintering of the specimens. The result is the production of so-called highly porous cellular materials, the structure of which copies the three-dimensional rod structure of the polyurethane foam.

A unit cell of a highly porous cellular material can be represented in the first approximation as a dodecahedron consisting of 30 ribs (tension members) and 20 nodes. The basic failure mechanism of a highly porous cellular material under compressive loading is that of loss of stability of the tension members.

Considering that with restricted lateral deformation all of the nodes can move only in the vertical direction and the position of the rods is a random factor, the mean value of vertical applied force is $\overline{P} = nj P_{kp}$, where P_{kp} is the critical force applied along the axis of a tension member; nj-0.5 is the orientation factor. The stress in the specimen at which the process of loss of stability starts in the tension members can be defined as

$$\sigma c = knjnpP_{kp}, \quad (1)$$

where n_p is the number of tension members per unit area, np = (10Vo)2/3 = 1.194 l2; k is an empirical coefficient considering the techn logical specifics of producing the highly porous cellular material specimens (porosity of the tension membe , nonuniformity of cell dimensions, decrease in tension member strength during sintering).

Depending on the volumetric content of compact metal $C = \rho_o \pi k$, where π_o is the density of the highly porous cellular material specimen; π_k is the density of the compact metal, the following expressions have been derived for the critical load in the elastic, elastic-plastic and plastic areas of deformation:

$$P_{кр} = \begin{cases} 0{,}185\, E F C, & C \le C_{пр} \\ 1{,}33F[\sigma_т - 0{,}25\sigma_{пц} - 2{,}32\, \sigma_{пц}\, E(\sigma_т - \sigma_{пц})C^{-1}], & C_{пр} < C < C'_{пр} \\ \sigma_т F, & C \ge C'_{пр} \end{cases} \quad (2)$$

where CMpr, C'F14pr are the limiting contents of metal in the highly porous cellular material specimen,

$C_{пр} = 5{,}37\sqrt{\sigma_{пц}/E}$, $C'_{пр} = 6{,}2C_{пр}$, E, $\sigma_{пц}$, $\sigma_т$ are the modulus of elasticity, proportionality limit and yield point of the compact metal, F is the cross-sectional area of a tension member.

Experiments on compression of highly porous cellular material specimens in a rigid housing were conducted in order to check these equations. Cylindrical specimens were made by saturating polyurethane foam with a metal-containing suspension based on iron powder. In order to consider the force of friction, the housing was installed on a calibrated rubber bushing. The critical load was the stress measured at σ0.2. Based on the characteristics of the compact metal ρk = 7.68g/cm3, E = 223 GPa, σF14t = 100 MPa, σF14pc = 80 MPa, the calculated values of limiting metal content were CF14pr = 0.19ρ10-2, C'F14pr = 0.012. The specimens were tested in the range of change of C from 0.02 to 0.15, and therefore the experimental data were approximated using the third equation from (2). Substitution into (1) yields the final form for prediction of the strength properties of highly porous cellular material specimens

$$\sigma_c = 0.457kc\sigma_{Ц} \quad (3)$$

We note that in deriving equation (3) we used the relationship between the area and length of a tension member F/l2 = 0.766, which is correct for dodecahedral cells with arbitrary dimensions. One result of equation (3) is that the load-bearing capacity of highly porous cellular material specimens is independent of the cross-section of a tension member, its length and the cell diameter, and is determined only by the volumetric content of metal and its strength characteristics. Analysis of the experimental variation of practical load as a function of volumetric content of metal shows that at k - C 01 it approximates the linear variation of (3) quite well, allowing these equations to be suggested for prediction of the strength properties of highly porous materials.

UDC 539.41:629.7

THEORETICAL AND EXPERIMENTAL STUDY OF HIGHLY POROUS PERMEABLE CELLULAR METALS AND THREE-LAYER STRUCTURES MADE OF THEM

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(RITTs PM, Perm)

The problem of assuring operational reliability for structures of lightweight three-layer panels is in many cases solved by the use of fillers of highly porous cellular materials instead of plastic foam.

In order to allow optimal design of three-layer panels based on highly porous cellular materials and to predict their properties as functions of usage conditions, calculations of the mechanical characteristics of the fillers were undertaken for various values of micro- and macrostructure parameters. The experimental studies performed of the behavior of highly porous cellular material specimens made of nickel in compression, extension and flexure and the results obtained agree satisfactorily with an accuracy of 15-20T% with the calculated data.

Tests were performed on bending and longitudinal compression of the three-layer panels obtained by soldering, with the porosity (P) of the filler 95.1-97.5% and the cell size (dc) from 1.2 to 4.5 mm. It was found that when the liners used were soft nickel plates 0.1 mm thick the panels characteristically lost stability at filler parameters P % 96% and dc & 2.7 mm, with total loss of stability at P & 96% and dc % 2.7 mm. When plates of type 12Kh18N10T stainless steel 0.3 mm thick were used, total loss of stability of the panel occurred with all types of filler, with significant intermixing of the outer layers and crushing of the filler.

These tests were used to establish the optimal geometric, structural and mechanical characteristics of three-layer panel elements for certain practical loading systems.

UDC 620.22-419

DEFORMATION PROPERTIES OF METAL KNIT REINFORCING GRIDS

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Design of products made of composite materials reinforced with knit metal grids requires preliminary estimation of the deformation properties and elastic characteristics of the composite materials as functions of the grid structure, loop shape, number of threads per bundle forming the loops, rigidity of wire, et cetera. In this work, numerical methods are used to solve the problem of determining the deformations and effective elastic characteristics of knit metal grids with "lasting" structure.

These grids, manufactured by textile techniques, have regular repetition of loops forming columns and rows of loops. When loaded in the plane of the grid, the loops deform basically by bending as flexible rods, allowing significant displacement to develop. The deformation of the loop can be arbitrarily reduced to solution of the planar problem of determining the shape of the elastic line of a flexible rod of constant cross section operating in the elastic area.

The shape of the axis of an undeformed rod in a knitted loop can be represented by a periodic line of variable curvature. Due to the symmetry of the loop, we can study one fourth of a loop. The differential equations defining the shape of a loop are written relative to the angular coordinate θ, which is a function of the arc length S:

$$\frac{dx}{dS} = \cos\theta(S), \qquad \frac{dy}{dS} = \sin\theta(S), \qquad (1)$$

where θ is the angle between a tangent to the axis of the undeformed loop rod and the axis x, directed along a loop row; y is perpendicular to x (along a loop column). The variation of coordinate y as a function of arc length S is

$$y = A \sin\frac{\pi S}{2a}, \qquad (2)$$

where a = 1/4 of the loop length, A is the maximum value of coordinate y.

Based on equations (1, 2), angle θ is determined by the expression

$$\theta = \arcsin\left(A\frac{\pi}{2a}\cos\frac{\pi S}{2a}\right). \qquad (3)$$

Considering the effect of the tensile forces in the plane of the grid, we obtain a system of differential equations with variable coefficients for the case of extension of the grid along the loop columns and along the loop rows.

We performed computer calculations with input parameters representing the shape of a loop and the size of the load. The calculations yielded the form of the elastic loop line and the movement of structural elements as functions of the applied load. We also determined the elastic deformations, effective elasticity moduli and effective Poisson ratios. By effective values of these quantities we mean the coefficients relating the stresses and strains.

The calculation demonstrated that for a knitted metal material with "lasting" structure, the rigidity in the direction of loop columns is greater, the more the undeformed loop is stretched in this direction while, conversely, broader loops increase rigidity in the direction of the loop rows. We note that the effective elasticity moduli and Poisson's ratio obtained by calculation are not constant and depend on the applied load and loop shape, while the effective grid transverse deformation factor exceeds the maximum value of Poisson's ratio for ordinary materials, which is 0.5.

The results of the calculation were compared with experimental data obtained by stretching "lasting" grids of steel and copper wire. The good agreement of calculated and experimental data indicate that this method is acceptable for engineering computation in the design of composites.

UDC 593.385

MODELING OF MECHANICAL BEHAVIOR OF FLEXIBLE CABLES FROM THE STANDPOINT OF TUNABLE SYSTEM MECHANICS

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The concept of a composite as a two-component system consisting of a matrix plus reinforcing fibers can in some sense be applied to cables which consist of metal current-conducting cores and protective insulating layers (shells).

However, if the current-conducting cores of a cable can be considered an analogue of the continuous fibers in a unidirectionally reinforced composite (the current-conducting cables, twisted up of copper wire, have a diameter of about 10-3 m, while the diameter of the fibers in a composite is closer to 10-6 M), the matrix in the accepted sense is missing (the insulating layers are not bound together and do not assure compatible deformation of the cable elements).

Therefore, we should think of a cable as a composite only from the standpoint of its heterogeneity, related to the presence of a certain degree of orientation of the macroheterogeneous layers (the orientation in a cable follows a helical line).

To study the mechanical behavior of a cable, it has been suggested that it be considered a heterogeneous rod, modeled by a hereditary elastic medium.

A number of studies have been published establishing that the theoretical unloading curves differ from experimental curves if the experimental results are processed by models of the hereditary theory of elasticity (such as the integrated equations of Volterra with Abel's kernel).

However, use of the theory of tunable-system mechanics can achieve a high degree of experimental data processing accuracy. It has been shown that the greater the value of the structural tuning parameter κ($0 < \kappa < 1$), the greater the resistance of a cable to deformation.

IV. TECHNOLOGICAL MECHANICS AND TECHNOLOGY OF COMPOSITE-MATERIAL PRODUCTS

UDC 629.735.33

TECHNOLOGICAL MECHANICS OF DEFORMED COMPOSITE MATERIALS

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The past decades have seen a great increase in the use of a wide variety of composite materials. These have been primarily "classical" uses, in which the material and the structure or element made of it were manufactured in a single technological cycle. Shape modification methods used for various composite material systems may vary — from winding to layup with subsequent molding, pultrusion (for polymer composites) to casting, stamping and forming (for metal and ceramic composites). Saturation can be used with any type of matrix.

Some composite-semifinished product systems in the form of sheets or plates can be obtained by technological processes such as soaking, pressing and explosive welding. The area of application of these materials may depend on their deformation capability. Therefore, deformable composites are of the greatest interest.

Achievement of the potentially great properties of composites in a structure requires that the influence of the technological operations as a flat semifinished product is converted to a part or finished product be considered. These problems can be solved within the framework of process mechanics — the area of study which analyzes the changes in properties of materials as they are converted from semifinished goods to finished products, depending on the various technological processes used.

We should probably refine the concept of deformable composites. Obviously, the great variety of composites, regardless of type of matrix and reinforcing elements, can be plastically deformed to some extent during technological processes. The major factors determining this capacity for deformation include the presence of a plastic matrix or plastic structural components (for multilayer composites), the capacity for converting a matrix to the plastic state (for thermoplastic composites). The properties and shape of the reinforcing components in composites determine the possible limits of deformation. It follows from all of this that many composites are deformable.

Let us briefly analyze deformable composites, most frequently used in production and acting as typical representatives in terms of type of matrix and reinforcing elements.

Composites consisting of layers of various metals with clear phase interfaces are layered metal composites. Sheets and plates can also be obtained by methods of saturation or explosive welding. The combination D16-VT1-0 (aluminum-titanium layered metal composite), Kh18N10T-AD-1 (aluminum-stainless steel metal composite) and AD-1-M1 (aluminum-copper metal composite) are widely used.

Composites containing metal layers on the outer surface, while the inner layers are essentially polymer composites, with a reinforcement consisting of a fabric or various types of fibers, are also used. These are called metal-polymer composites.

A fiber metal composite material is promising for use as a deformable composite. The fiber usually runs in a single direction. The basic methods of making these composites are pressing for brittle fibers, saturation, explosive welding for plastic fibers. Sheets containing fibers of boron, steel and aluminum or magnesium matrices are used.

In recent years, thermoplastic materials have come into increasing use as composite materials. Based on their mechanical properties, some thermoplastic composites are equal to cured polymer composites with thermosetting matrix.

Obviously, these composite materials have a great variety (x) of combinations of components M and their volumetric fraction (V) in the composites — X(M, V). Considering the technological limitations related to the possibility of producing composite semifinished goods of the desired quality K, and at certain

cost (S), we obtain the subset X(M, V, K, S) of possible composite materials.

The use of a deformable composite material is determined by a variety of goals and a system of physical-mechanical properties. Consequently, we must refine the major goals to be achieved by the use of composites. These include reduced weight, improved characteristics of the composite material influencing the basic usage properties (damping capability, wear resistance, conductivity, et cetera). We shall refer to these requirements as operational (O), meaning by this the system of possible characteristics, so that we obtain the following set for selection of a composite material: X''(M, V, K, S, O). This is the typical decision-making hierarchy used in the "classical" application of composite materials.

For the case when composite materials are used as sheet semifinished goods, the deformation capability of the composite material being designed is not considered (X → X' → X''). We must additionally consider the structural limitations determined by the shape of the part. These usually include the maximum (or minimum) radii of curves, resulting from the limits of deformation of the composite material and its individual components. Thus, the subset of possible versions X'' is constricted further to the subset X'''. Obviously, X''' ⊆ X'' ⊆ X' ⊆ X. A simple logical diagram of decision making in the design of products of composite semifinished goods is shown in Figure 1.

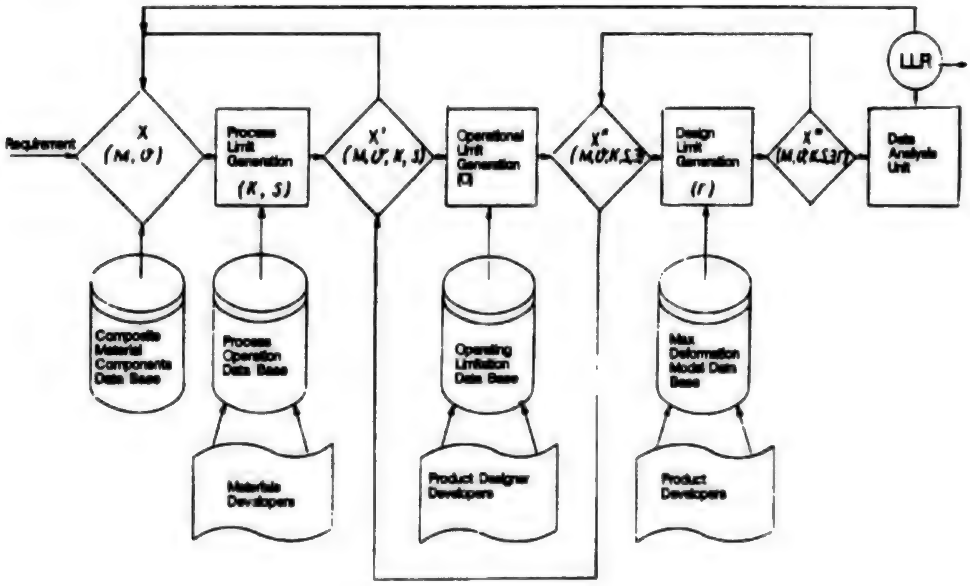

Figure 1

Logical Diagram of Decision Making in Planning Products of Composite Intermediate Products

Thus, a number of specifics can be noted of the development of products of deformable composite semifinished goods:

1. The basic methodological principle of product design is systematic analysis of date files, since they are significantly greater than when homogeneous materials are used.

2. In the development of an RP, depending on the specifics of the object to be designed (the product, its production process, composite material characteristics), we must determine the hierarchy for decision making and establish the basic optimization criteria.

3. In studying composites, data must be obtained on the combination of basic operational and process properties as functions of the structure of the material considering the influence of technological production process operations on the semifinished product and the composite finished product.

UDC 539.3:519

DEVELOPMENT OF MODELS OF DEFORMATION OF METAL COMPOSITES IN BENDING

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Metal-matrix composite materials are quite promising for use in modern machine-building products. The problems of producing sheet composite materials with high specific strength and rigidity characteristics has been solved. However, the use of parts made of composite sheet materials in machine building is limited by the lack of technological processes allowing the production of products with the necessary dimensions and strength properties.

In the design of efficient technological processes, we must understand the mechanics of metal-matrix composite behavior in plastic deformation. We suggest the development of universal methods for design of technological processes for bending of metal-matrix composites, based on determination of the parameters of the stress-strain state by means of the method of finite elements.

The area of the material subject to deformation was selected for the composition of a calculation plan. It was assumed that the placement of fibers was symmetrical with respect to the coordinate axes.

The problem was reduced to a two-dimensional one. Rectangular and rhombic placement of fibers was studied (Figure 1).

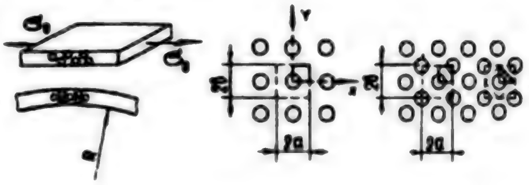

Figure 1

The following assumptions were made in the statement and solution of the problem:

- the fibers are uniformly distributed within the matrix and have quadratic packing;
- bonding between fibers and matrix is ideal;
- flow of the matrix material occurs under conditions of planar deformation, so that its dimensions are an order of magnitude less than the bending radius.

In our analysis of the process, we studied several calculation plans. In the first case, the cell of the composite material was one quarter of a boron fiber (as a result of the symmetry mentioned above) plus the adjacent matrix material. In the second case, the boron fiber was considered an absolutely rigid body, while the mechanical bonding of boron and aluminum was assumed ideal.

The area studied was divided into finite elements by the use of an automated data preparation system (Figure 2). The initial data for automatic subdivision were the coordinates of the boundaries of the area and the zone with various spacing steps. As a result, the system defines the coordinates of nodes, an array relating elements to nodes, and renumbers nodes to speed up the process of computing the rigidity matrix.

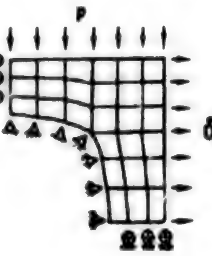

Figure 2

The boundary conditions in the calculation plan (Figure 2) were assigned by fixing the nodes to prevent movement or by limiting movement in one of the coordinates. A uniformly distributed load of various sizes was applied to the nodes.

As a result of the computations we determined the shear and tangential stresses, the intensity of stresses and strains, and the field of displacements for the coordinates.

An application software package was developed to model and compute the process of bending of metal-matrix composites, allowing us to establish the influence of process bending parameters on the stress-strain state of the material. The results of the modeling allowed us to estimate the nonuniformity of stresses and strains in the area of the bending section, to predict

the appearance and development of cracks in the material during failure and to demonstrate promising systems for increasing process plasticity. The conclusions were confirmed by experimental metallographic studies of the process of failure of a metal-matrix composite during bending.

UDC 539:678.02

TECHNOLOGICAL MECHANICS OF COMPOSITE STRUCTURES OBTAINED BY POWER WINDING

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In developing products of fiber composites, due to the great sensitivity of their physical and mechanical properties to the parameters of their manufacturing proces[illegible] [illegible]ed arises to study the influence of these para[illegible] on the kinetics of the stress and strain fields crea[illegible] composite semifinished goods. In the early stages of this process, which ends with the formation of a composite semifinished product, the kinetics of these fields are determined by purely mechanical effects (power winding, pressing, winding on a mandrel, et cetera).

Problems related to mathematical modeling of the physical and mechanical processes occurring in the formation of a composite semifinished product by power winding have been studied either in simple statements for "dry" winding[1,2], based on which it is impossible to determine the kinetics of the stress and strain fields of the semifinished composite product when products of complex shape are created, with structural heterogeneity of the defining relationships of the composite material due to the arbitrary mandrel shape, or within the framework of the phenomenological statement of "wet" winding[3,4], which requires experimental determination of additional equations, a difficult experimental task for a composite material semifinished product. Therefore, the process mechanics of composite materials obtained by power windings is in its earliest stages. It is therefore necessary to construct a unified methodology for producing mathematical models to describe the process of formation of a composite semifinished product by power winding, to consider the specifics of this process, as well as the kinetics of the stress-strain state of a composite semifinished product related to the constant increase in the quantity of prestressed reinforcing filler per unit of semifinished product surface area.

In order to construct such mathematical models in this work we use the method of averaging of processes in periodic media presented in [5]. We also suggest an algorithm for producing a closed system of equations describing the kinetics of the structurally mediated stress and strain fields in the semifinished composite product during formation on a generally deformable mandrel with arbitrary parameters. An algorithm is suggested for producing averaged defining equations in explicit form. IN order to determine the components of the effective tensors of the elasticity and viscosity moduli for dry and wet winding by the method of [5], we must solve the problem in a periodic cell. It is shown in this work that, due to the invariance of the equations in a cell with respect to rotations of the axes of a specially selected local Cartesian system of coordinates by angle π, the solution of the problem for a cell is reduced to determination of nine components of the effective tensors of the defining equations (the medium of the semifinished product is orthotropic). In order to determine these coefficients for the case of dry power winding, we must solve six problems from elasticity theory for one quarter of a periodic cell. In this work these problems are solved by the method of potential theory.

During modeling of the technological process of power winding of a composite semifinished product on a thin-shell mandrel (for the manufacture of thinwall combined shells), the averaged system of equations for the semifinished product can be reduced to two-dimensional equations. In this work this reduction is performed on the basis of a variational statement of the problem of interaction of the composite semifinished product and the deformable mandrel within the framework of the Kirchhoff-Love model for the mandrel and expansion of the vector of displacements of the composite semifinished product into a series with respect to Legendre polynomials. The vector of displacements of the semifinished product is presented as the sum $U = V + w$, where $U = v + z(n^*_o - n_o)$, $z \geq 0$ (v is the vector of displacements of elements of the face surface of the mandrel, z is the normal coordinate read along a perpendicular to the face surface of the mandrel, n_o, n^*_o is the normal of the deformable mandrel at an instant in time) is the vector of displacements corresponding to the Kirchhoff-Love model for a two-layer shell, one of the layers of which is the composite material semifinished product being built up.

The concept of the displacements vector which is introduced allows the system of equations to be written for a two-layer shell in quasilinear form rela-

tive to the moments $\overset{(k)}{w}$ of the series with respect to Legendre polynomials of the function $\bar{w}$.

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UDC 539.3

STRESS, STRAIN AND DISPLACEMENT FIELDS IN THREE-LAYER SHELL WITH OUTER LAYERS OF FIBER COMPOSITE MADE BY POWER WINDING AND AFTER CLEAVAGE

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1. One progressive method of manufacturing three-layer shell elements with outer layers of fiber composites consists of the following steps:

- power winding on a rigid mandrel in which the face surface σ is described by the equation $\bar{r} = \bar{r}(x^1, x^2)$ (x^i are the Gaussian coordinates on σ) for the lower load-bearing layer with thickness $2h_{(1)}$ and middle surface $\sigma_{(1)}$;
- layup of a honeycomb filler with thickness 2h measured in the direction of the perpendicular $\bar{n}$ to σ;
- power winding of the upper load-bearing layer with thickness 2h(2) and middle surface $\sigma_{(2)}$ onto the filler;
- heat treatment of the assembled pack;
- removal of the finished product from the mandrel and cutting of the product into elements of the required shape.

Due to the formation of stress and strain fields in the layers of the three-layer shell in all of the stages described above, after the product is removed and cut its shape is distorted. This requires that we solve the problem of determining the shape of the mandrel surface σ required to achieve the desired final shape characteristics of the product.

2. A series of mathematical models and the corresponding solution equations were developed to determine the fields of stresses, strains and displacements arising in the shell in the various steps of its manufacture. These equations are based on the assumption that as the thin bottom layer is wound on the mandrel the stress state which arises in it can be considered a zero-moment state, and the method of averaging processes in periodic media developed in [1] can be used to determine the average initial stress tensor $\overset{o}{\sigma}{}^{ij}_{(1)}$ and the effective component of the elasticity modulus tensor of this layer $\mathring{A}^{ijkl}_{(1)}$

The average effective elastic characteristic tensor $\mathring{A}^{ijkl}_{(2)}$ of the composite material semifinished product in the upper layer is determined similarly. In order to determine the stresses $\overset{o}{\sigma}{}^{ij}_{(2)}$ strains $\overset{o}{\varepsilon}{}^{(2)}_{ij}$ and displacements $\overset{o}{U}{}^{(2)}_{i}$, $\overset{o}{w}{}^{(2)}$ in the upper layer within the framework of the assumption of its zero-moment nature, as well as the stresses $\overset{o}{\sigma}{}^{\alpha\beta}$, strains $\overset{o}{\varepsilon}_{\alpha\beta}$ and displacements $\overset{o}{u}_i$ in the filler, appearing in it during power winding of the upper layer above it, a system of three two-dimensional differential equations is constructed and solved for the functions $\overset{o}{u}{}^{(2)}_{i}$, $\overset{o}{w}{}^{(2)}$. The construction utilizes the partial procedure suggested in [2], corresponding to continuous contact of the filler with the load-bearing layers as to displacements, simplified within the framework of the assumption of little change in transverse shear stresses $\overset{o}{\sigma}{}^{i3}$ in the filler on the coordinates x^i and zero displacement of the bottom layer due to its intimate contact with the mandrel. The model which is constructed can consider the kinetics of the stress-strain state in the filler and in the second layer during power winding.

3. It is assumed that in the process of heat treatment of the semifinished product assembled in the sequence described, the elastic characteristics of the binder material change, leading to a change in the load-bearing layers of the tensor components $\mathring{A}^{ijkl}_{(s)}$ $(S = 1,2)$ to the tensor components $\mathring{A}^{ijkl}_{(s)}$. In order to determine the latter, obviously, we could use the methodology of 1 as before. The changes evoked by the transition of $\mathring{A}^{ijkl}_{(s)}$ to $A^{ijkl}_{(s)}$ in the stresses

$\Delta^{o}_{\sigma}{}^{\alpha\beta}$, $\Delta^{o}_{\sigma^{(s)}}{}^{ij}$, strains $\Delta^{o(s)}_{\varepsilon ij}$, $\Delta^{o}_{\varepsilon\alpha\beta}$ and displacements

$\Delta^{o(2)}_{u}$, $\Delta^{o(2)}_{w}$, $\Delta^{o}_{u^i}$, Δ^{o}_{w} are determined based on the

two-dimensional equations mentioned above by replacing $\mathring{A}^{ijkl}_{(s)}$ with $A^{ijkl}_{(s)}$.

In the equations constructed previously[2], simplified within the framework of the assumptions we have made concerning zero-moment outer layers, little change in shear stresses σ^3 in the filler with respect to x^i, by considering stresses in the filler σ^{ij}, are used to describe the stress-strain state of the shell after heat treatment, its removal from the mandrel and cutting. The external load in these equations is the reactive force acting on the lower layer from the mandrel determined in the previous step, as well as the contour load applied to the layers along the lines of sections and formed from the stress tensors found in previous steps.

4. The basis of the mathematical model of the mechanics of deformation of the three-layer structure is sequential integration of the three-dimensional equations from the theory of elasticity, written for the filler with accuracy equivalent to $\delta^{\varphi}_{i} - \zeta B^{\varphi}_{i} \approx \delta^{\varphi}_{i}$ (z is the coordinate read from σ in direction $\overline{m}$, bj_i are the mixed components of the second metric tensor in σ) and simplified by introducing the assumptions $\sigma^{11} \approx \sigma^{12} \approx \sigma^{22} = 0$

$$\partial_z \sigma^{33} + \nabla_i \sigma^{i3} \approx \partial_z \sigma^{33} = 0,$$

which allows us to establish the rule of change of the displacements ui, w in the filler from z, to express them through the components of the displacement vectors of points $\sigma(s)$, $u_i(s)$, $w^{(s)}$, then to compute the components of the deformation tensor in the filler $\sigma^{\alpha\beta}$ within the framework of the general law of Hooke. In modeling the processes from stages one through four in the lower layer the displacements $\overset{o}{u^i}{}^{(2)}$, $\overset{o}{w}{}^{(2)}$ and $\Delta^{o(2)}_{u^i}$, $\Delta^{o(2)}_{w}$ are assumed to be zero.

All theoretical constructions are performed in the geometrically nonlinear quadratic approximation, allowing the linearized equations derived to be used to formulate problems of the stability of the equilibrium states studied within the framework of the Euler static stability criterion both after removal of the product from the mandrel and after it is cut into elements of the required shapes.

5. This methodology for modeling the changes in stress-strain state of a three-layer shell in all stages of its manufacturing process can be easily extended to the case of considering the moment stress-strain state in the outer layers. Within the framework of this same methodology we can construct a sequence of mathematical models for description of the kinetics of the stress-strain state in the manufacture of shell elements of fiber composite structures by power winding with arbitrary multilayer structure.

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UDC 539.4

PROCESS MECHANICS OF POLYMER COMPOSITE GEAR WHEELS

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One means of solving the problem of decreasing the metal consumption of structural elements is to replace them with composite material parts, specifically reinforced polymers. A number of the features of these materials (light weight, corrosion resistance, good strength, good damping capabilities, et cetera) give them advantages over traditional materials. These composite materials can be manufactured simultaneously with the creation of the structural elements made of them, allowing the structural specifics of the elements and their usage conditions to be considered in the stage of manufacturing the composites.

This article studies the problem of design and development of technology for manufacture of complex-shaped parts such as gear wheels from composite materials.

Existing polymer gear wheel manufacturing methods allow these wheels to be made of polymers reinforced with short (up to 5 mm) fibers. However, the load-bearing capacity of these gear wheels can be increased by reinforcing them wit continuous fibers in the area of maximum stress.

The theoretical foundation for the method of producing complex-shaped parts by this approach is the principle of quasisurface reinforcement of a curved structure[1].

The technical implementation of this principle is as follows. First, a cylindrical blank is wound and the gear wheel is pressed from preimpregnated tape or filaments of the polymer composite material with inner and outer fiber lengths equal to the perimeter of the gear wheel and the hub. The heated blank is then placed in the press mold, where the tooth profile is formed.

The manufacture of gear wheels requires special equipment which retains the reinforcing fiber in the desired position during pressing. A press mold has been developed for this purpose in which the gear wheel is pressed form thermosetting plastic or tapes of thermoplastic fiber. The position of the reinforcing fibers is preserved during pressing and feeding of the blank into the pressing cavity by the design of the press mold[2].

As we make the transition to manufacturing parts such as gear wheels of polymer composites (particularly tension-bearing parts of agricultural equipment chain drives), it becomes possible to replace rolling-surface bearings, used to carry tension wheels, with friction bearings, simplifying the technology of assembly of units and decreasing their cost. It has been suggested that this type of bearing be made of a metal ceramic (iron-graphite, bronze-graphite).

Elements of this type made of composite materials (gear wheels, friction bearings) must be designed considering the specific properties of the materials. Models have been suggested which consider these features.

The basis of the design of gear wheels for strength and rigidity is a cantilever-plate model. The use of equations from refined plate theory[3] has shown that considering the deformations of transverse shear and compression makes it possible to increase the load-bearing capacity of cantilever plates[4].

The calculations involved also consider the possibility of areas of less-than-ideal adhesion (between the center of a gear wheel and the wear-resistant coating, between reinforcing fibers and the binder) during the manufacture and use of the parts.

The design of parts operating in friction (chain drive roller and composite gear wheel, metal-ceramic bushing and shaft) must consider heat liberation and wear. In particular, the variation of temperature in the contact zone as a function of percent content of graphite in the composite antifriction material must be computed. We note that increasing the content of graphite per unit volume helps to decrease the temperature in the contact zone. Theoretical computations have been conformed by laboratory experiments.

The calculations presented in this article allow optimal process parameters to be selected for the manufacture of parts.

The method suggested was used to manufacture an experimental batch of tension members for use in beet-harvesting machine chain drives. The parts were tested under field conditions at a machine-testing station. The results of the tests showed that the experimental tension members had certain advantages over series-produced units, including longer life and greater reliability.

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UDC 621.7.044.2.001.57

MATHEMATICAL MODELING AND MULTIPURPOSE OPTIMIZATION OF PULSE TECHNIQUE FOR MANUFACTURING METAL MULTILAYER COMPOSITE PRODUCTS

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Pulse pressure methods (explosives, electrical explosion of a conductor, variable magnetic fields) are widely used for the manufacture of products of multilayer metal composite materials. Of these various pulse techniques, the method of producing composites by explosive loading occupies a special position, having the additional advantage of simplicity of implementation, not requiring complex and expensive equipment, as well as the ability to produce composite materials with variable strength of the interface between the composite components[1]. We note that the strength of the joints between composite components produced by pulsed loading is largely determined by the kinematics of the process, related to the movement of the energy transfer medium and the layers of the welded composite blank.

One technical problem which must be solved in the creation of multilayer products by pulse loading with variable interface strength is the need to organize the process so that similar collision conditions are achieved in all layers of a multilayer package. The experimental solution of this problem is quite cumbersome and requires a great deal of time. It is therefore quite important to develop systems for simulation of the process by computer, requiring the development of mathematical models of pulse processes and methods of multipurpose optimization.

This article presents an engineering and mathematical statement of the problem of throwing sheet and tubular solid energy-transfer bodies by the detonation products of explosives and kinematic collapse of multilayer composite material blanks with incrementally increasing mass (a set of plates or coaxial tubes) with these thrown bodies. A mathematical statement is also presented of the problem of multicriterion optimization of pulse technologies for manufacturing multilayer composite materials.

In the one-dimensional statement, the mathematical model of the process of collapse of the layers of a flat multilayer packet (composite material blank) in section *i* of motion when it is loaded by the detonation products of an explosive is described by a system of differential equations

$$\begin{cases} \dfrac{dx}{dt} = V, \\ \dfrac{dV}{dt} = \dfrac{P_{oi}}{C_{oi}^{3} M_i}\left(\dfrac{x+l}{l/D+t} - V\right)^3 \end{cases} \quad (1)$$

with the initial conditions

$x = x_{i-1}$, $V = V_{oi}$ where $t = ti-1$, (2)

where

$$M_i = \sum_{k=1}^{i} m_k, \quad t = t_{i-1}$$

such that

$$x_{i-1} = x(t_{i-1}) = \sum_{k=1}^{i} h_k \quad ;$$

$$V_{oi} = \frac{M_{i-1}}{M_i} V_i, \quad C_{oi} = C_{i-1} + V_{i-1} - V_{oi}, \quad P_{oi} = P_{i-1}\left(1 + \frac{V_{i-1} - V_{oi}}{C_{i-1}}\right)^3;$$

$$V_{i-1} = V(t_{i-1}); \quad C_{i-1} = \frac{\sum_{k=1}^{i} h_k + l}{l/D + t_{i-1}} - V_{i-1}; \quad P_{i-1} = \frac{P_{o\,i-1}}{C_{o\,i-1}^{3}} C_{i-1}^{3}$$

Here *l* is the height of the explosive charge; D is the detonation velocity of the explosive; m_k is the mass of plate k of the packet; mi is the total mass of the moving plates at the moment of collision i; x and V are the displacement and velocity of the plates of the packet; hk, (k =
I,i) are the initial gaps between the plates of the plates of the packet; *ti-1* is the moment corresponding to plate collision i-1; c and P are the speed of sound and the pressure in the explosion products at the explosion product-thrown plate interface; Coi-1 and Poi-1 are the initial values of C and P in movement section i-1. (The subscripts "oi'' and "i-1" with V, C and P correspond to the initial values of parameters representing the end of motion in section i-1).

A mathematical model of the process of collision of layers of a multilayer tubular packet in section i of motion with loading of the packet by detonation products is described by the system of differential equations

$$\begin{cases} \dfrac{dx}{dt} = V, \\ \dfrac{dV}{dt} = 2\left\{x \ln \dfrac{x^2}{x^2 - [R^2_{\text{нар}}(t_{i-1}) - R^2_{\text{вн}(i)}]}\right\}^{-1} \left\{V^2 \dfrac{R^2_{\text{нар}}(t_{i-1}) - R^2_{\text{вн}(i)}}{2[x^2 - R^2_{\text{нар}}(t_{i-1}) + R^2_{\text{вн}(i)}]} - \right. \\ \quad \left. - \dfrac{16 P_0}{27 \rho_{\text{вн}_i} D}\left(\dfrac{l + R_{\text{вн}(i)} - x}{t} + V\right)^3\right\} - \dfrac{V^2}{x} \end{cases} \quad (3)$$

;

with the initial conditions

$$V > \left(\frac{dR_{n(t)}(t_{i-1})}{dt} \right)_{0i} \quad t = t_{i-1}, \tag{4}$$

where x = RH(1)(t) is the outer radius of the first layer; V is the velocity of the outer layer of the packet; $R_{H(1)}(t_{i-1})$ is the outer radius of the first layer at the moment of collision i-1; $R_{V0(i)}$ is the initial inner radius of layer i; l is the height of the explosive charge; $\rho 0$ and D are the density and detonation velocity of the explosive; ρ_{cpi} is the average density of the moving compound tubular shell in sector *i* of movement

Problems (1)-(2) and (3)-(4) were solved by the fourth order Runge-Kutta method on an SM 1420 computer. The computer programs for numerical solution of the problems provide for automatic adjustment of the integration step, allowing us to find the moments of collision of elements with predetermined accuracy. The program was written in FORTRAN-IV.

Using the mathematical models produced, it is possible to formulate the technical problem of organizing the parameters of pulse processes for manufacturing multilayer composites, assuring collision conditions in each collision event close to those assigned, as a mathematical problem of multiple-criterion optimization of the pulse process, which can be implemented by soundings in the space of parameters2.

Thus, for example, formulation of the multiple-criterion problem of optimal design of a process for manufacturing an explosively welded flat packet consisting of n plates assuring that the collision velocity in each collision event will be Vi, (i = I, (n-1)) in the interval v_0 Gæ DV, is as follows:

- □ given a vector of process parameters $\bar{X} = \{x1, \ldots, x_m\}$ (the components of the vector are the parameters of the explosive, the gaps between the plates and the characteristics of the welded plates), which must be selected by the "best" manner;
- □ given are the parametric limitations defining the m-dimensional parallelepiped π in the space of parameters;
- □ given are the optimization criteria

$$\Phi_i = |V_i - V_0|, \qquad i = \overline{I, (n-I)}$$

- □ given are the optimization characteristics

$$\varphi_1 \rightarrow \min \text{ where } i = \overline{I, (n-I)}$$

- □ given are the criterial limitations

$$|V_i - V_0| \leq \Delta V, \qquad i = \overline{I, (n-I)}$$

- □ select a combination of parameters satisfying the optimization characteristics and the criterial limitations.

To design a pulse technology for the manufacture of multilayer tubular products of composite materials, we must add to the problem formulated above the condition of assuring the required geometry of the layers of the welded product. If necessary, otehr conditions can be added to the optimization problem (such as the condition of constant expenditure of kinetic energy in plastic deformation of the welded layers as they collapse in each collision event).

The authors have developed an application software package to implement these problems, allowing automation of the procedure of multipurpose optimal design of pulse processes for the manufacture of multilayer sheet (up to 23 layers) and tubular (up to 10 layers) composite material products with predefined layer geometries. The optimization method used is the method of sounding the space of parameters in interactive mode. The output information is printed in a form convenient for the end user (composite material process engineer). The software package is intended for SM 1420 computers with at least 128 Kwords of memory and includes software models written in FORTRAN-IV for the OS-RV operating system version 3.0 and higher. The result of optimal design of a composite material process using this software package is a set of near-optimal versions of its organization. Selection of the single best version is then performed by the decision-making person by a heuristic method.

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UDC 539.3:519

MATHEMATICAL MODELING AND INVESTIGATION OF COMPACTING OF FIBER COMPOSITE MATERIALS WITH METAL MATRIX

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The quality of unidirectionally reinforced fiber composite materials with metal matrix obtained by solid-phase compacting depends essentially on the compacting conditions.

The interrelated processes of compacting a packet blank and forming a strong joint are largely determined by the nature and amount of stress and strain both at the microscopic level, i.e., in the volume occupied by a unit cell, and for the entire volume of the packet blank.

Due to the regular nature of the placement of the fibers, the solution of the problem of compacting fiber composite materials at the unit cell level can be extended to the entire volume of the composite, and such integral characteristics as the compacting force can be obtained by adding them for the entire set of cells.

At present, due to the small dimensions of a unit cell and the lack of equipment for the purpose, experimental studies of the stress-strain state at the interface between the fiber and matrix and within the matrix is not possible. Therefore, the development of a mathematical model of compacting of fiber composites with a plasma-tooth sputtering matrix at the level of the unit cell is an important problem.

In this work, we have developed a mathematical model for the compacting of a fiber composite material based on the method of finite elements.

The mathematical model allows analysis of various versions of packet designs: reinforcing fiber — foil matrix, fiber — combined matrix consisting of alternating foil and plasma-tooth sputtered layers. It is also possible to consider the type of packing of the fibers: hexagonal or tetragonal (Figure 1).

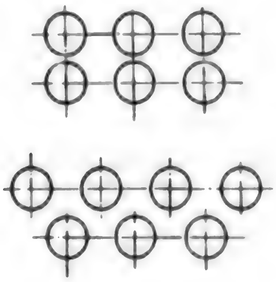

Figure 1

The fiber in this case is considered rigid (elastic deformations are ignored.

The behavior of the compact component of the matrix (the foil) was described by a system of St. Venant-Mises plasticity equations. The behavior of the plasma-tooth sputtered material was described by means of the theory of plasticity of porous (plastically compressible) materials.

The system of equations was digitized by the Bubnov-Galerkin method. The area of the solution was divided into tetragonal isoparametric elements with the quadratic approximation.

The system of algebraic nonlinear equations produced was solved by the method of successive approximations for each time step. The configuration of the element grid was deformed according to the motion of the matrix material.

As a result of the solution of the problem for each time step, we obtained the fields of distribution of the stresses, strains, velocities and density of the porous component of the matrix through the cross section of a unit cell, as well as the stresses at the interface between fiber and matrix.

An experimental check was performed of the computed results for compacting of a fiber composite material with an aluminum matrix in a press with a set speed of movement of the plates (system with forced deformation).

Comparison of photographs of microscopic sections of the material specimens obtained for various stages of the compacting process with the computed configurations of the element grid showed good agreement.

Comparison of computed and experimental variations of compacting force as a function of the degree of compacting confirmed the adequacy of the mathematical model.

A mathematical model adequate to the real process was used to study the process of compacting an aluminum-boron fiber composite material.

The studies were performed by numerical mod-

eling using a second order experimental plan.

Regression equations were obtained for certain characteristics of the compacting process as functions of temperature and deformation rate; in particular, a regression model was constructed for the compacting force.

The influence of process parameters on the distribution of normal and shear stresses over the surface of the fiber was analyzed.

When fiber composite materials with plasmatooth sputtered or combined matrix are compacted, there is significant interest in the distribution of density through the cross section of a unit cell. It was noted that each type of fiber packing — hexagonal or tetragonal — corresponds to a different distribution of matrix material density and stress at the fiber-matrix interface.

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STUDY OF FORMATION OF REGULAR FIBER PACKING AND ITS INFLUENCE ON MECHANICAL PROPERTIES OF BOROALUMINUM MATERIAL

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The elimination of initial porosity during compacting of a fiber composite material with a porous plasma-tooth sputtered matrix results from the approach of neighboring fiber layers. The result of this process is the formation of a certain regular layup. The tetragonal and hexagonal types of fiber layup used in theoretical analysis are idealizations of the true fiber-composite material structure and are usually not observed in practice. Usually, the cross section of a fiber composite material includes a continuous sequence of transitional types of fiber layup. Each "intermediate" or "ideal" version of layup contains objective information on the mechanical properties of the material since, on the one hand, the mutual placement of the fibers determines the redistribution of stresses during loading of the material, while on the other hand it represents the development of the process of compacting a unit cell and, therefore, the mechanical properties of the matrix.

The purpose of this work was to determine the degree of regularity of packing of the fibers of a composite material as a function of the technological parameters and their influence on the mechanical properties of boroaluminum.

As the criterion or parameter for quantitative evaluation of the mutual placement of fibers in neighboring layers in the sense of determining the packing, we suggest the packing parameter $P = l_1/S$ (Figure 1), where S is the horizontal spacing used in placement of the fibers in the material, while l_1 is the lesser of the arms ($l_1 < l_2$), obtained by projecting the centers of the fibers from a layer onto a line below the layer. The parameter was averaged for the series and used to describe the nonuniformity of placement of the fibers in the layers. The dispersion of the packing parameter P determined for various layers of the cross section was used to provide a quantitative estimate of the nonuniformity of packing in the layers.

Experimental studies yielded the variation in dispersion of the packing parameter as a function of all of the basic technological parameters (compacting by hot pressing). Due to the large number of factors which had to be considered, methods of experimental planning and mathematical statistics were widely used. Analysis of the equations derived revealed the variable influence of the maximum compacting pressure on the dispersion of the packing parameter. The design of the composite material blank, i.e., the volumetric fraction of the fiber and the ratio of foil and plasma-tooth sputtered parts of the matrix (Figure 2) was also found to influence this quantity strongly.

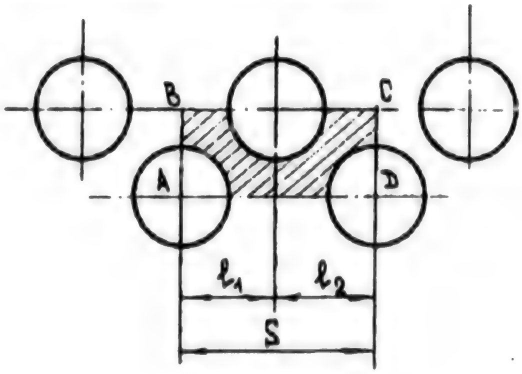

Figure 1

Since the fiber packing produced as a result of compacting influences the mechanical properties of the boroaluminum material in two directions (changing the fracture mechanism by the mutual placement of fibers and changing the mechanical properties of the porous matrix), there is interest in determining the predominant influence of one or the other factor.

For this purpose, we studied the influence of regular placement of the fibers in the transverse cross section of the material (with unchanged level of mechanical properties of the matrix material) on the properties of the boroaluminum by simulation modeling of the behavior of the material under load[1]. The change in the placement of the fibers occurred in bands determined from the results of the experiments outlined above.

When calculations were performed, the basis used was a quasi-three-dimensional single-band model of the behavior of the composite material in extension along the length of the fiber. The model was adjusted by considering the specific packing geometry of the

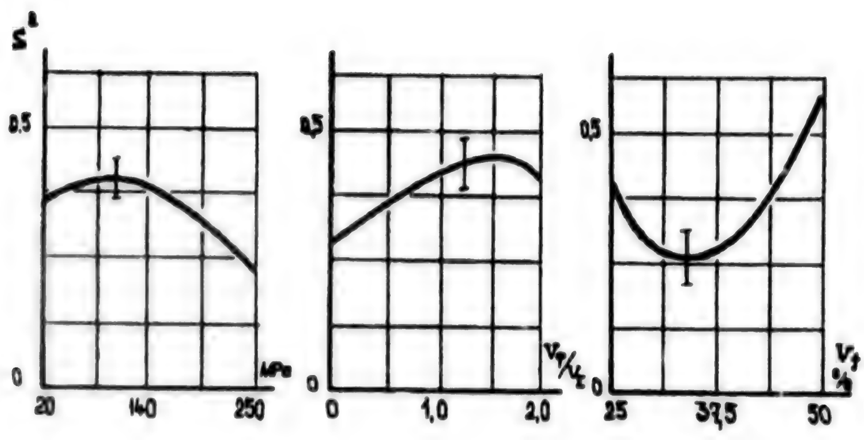

Figure 2

fibers obtained during manufacture of the actual material. The results of the calculations showed that a change in packing of the reinforcing fibers alone, preserving the other conditions unchanged, can lead to a change in the strength of the composite material in extension along the length of the fibers by 5-10%. We can therefore conclude that the type of packing of the fibers influences the longitudinal tensile strength to a greater extent by changing the mechanical properties of the matrix than by changing the failure mechanism.

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FORMATION OF INTERFACES IN FIBER COMPOSITE MATERIALS WITH TITANIUM MATRIX

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The manufacture of fiber composite materials with titanium matrix can be undertaken by various processes depending on the type (ceramic, metal) and form (fiber, cord, wire) of the reinforcing material. One must consider the great chemical affinity of titanium for gases and the high compacting temperature of fiber composite materials. In practice, fiber composite materials are frequently manufactured in two stages: preliminary formation of a semifinished product with final manufacture of the fiber composite material from the semifinished product.

For example, it is possible to produce fiber composite material with fibers of boron or silicon carbide by preliminary plasma-torch spraying of the matrix and subsequent hot pressing of packet blanks of plasma semifinished monolayers1. It is desirable to apply coatings of carbides on fibers to decrease the loss of strength upon exposure to heat and mechanical stress. It is possible to produce fiber composite materials with these ceramic fibers only by hot vacuum pressing of foil plus fiber packet blanks, with good quality materials obtained by proper selection of temperature, time and force parameters2.

The fiber composite material manufacturing conditions are evaluated by determining the strength properties in the longitudinal and transverse directions with respect to the reinforcing fibers and the size of the reaction zone at the fiber-matrix interface1. This zone in fiber composite materials with ceramic fibers consists of intermetallides, while in materials with metal reinforcing fibers it consists of solid solutions3, 4.

One feature of the production of fiber composites with carbon fiber is that this fiber is a cord consisting of 5,000-10,000 filaments each with a diameter of 5-8 μm. The high reactivity of titanium for carbon requires the use of vacuum hot pressing of a semifinished product consisting of a mixture of preliminarily oriented discrete carbon fibers and titanium powder at temperatures higher than the polymorphous conversion point. A study is made of the influence of barrier coatings (silicon carbide, titanium carbide, et cetera) on the process of breakdown of the fibers observed as the semifinished product is compacted. It is established that the mechanical properties of the fiber compact material are more strongly influenced by the length of a discrete fiber than by barrier coatings.

The use of powdered titanium leads in the initial stage of compacting to interactions between the components at individual points on the fiber surface. Furthermore, the appearance and growth of titanium carbide are most probable in locations of surface defects, leading to fragmentary formation of titanium carbide on the fibers. The carbide formed, acting as a stress concentrator, leads to breakup of fibers during compacting of the semifinished product. Subsequently, when a continuous layer of carbide forms on the fibers, the length of the discrete fibers is stabilized and is almost independent of isothermal holding time during hot pressing. These studies indicate that regardless of isothermal holding for hot pressing of titanium-carbon materials the length of the discrete fibers is sufficient to achieve up to 95% of the strength of continuous fibers. The basic advantage of titanium fiber composite materials reinforced with wires is their ductility and the possibility of shaping them with significant degrees of compression. Titanium-molybdenum wire composites were obtained by transverse hot rolling in a vacuum. Regulation of the temperature, speed and deformation during rolling allowed the development of recrystallization processes, diffusion processes and the rate of formation of new phases between the wire and matrix to be controlled. Rolling was performed at temperatures corresponding to the ($\alpha + \beta$) area with high total compression. The strength properties in the transverse direction correspond to the strength of the titanium matrix, while the strength of the fiber-composite material in the longitudinal direction was at the level of the design strength with good plasticity. Fracture was viscous in nature5.

Titanium was reinforced by tungsten wires by the use of welding in the solid state with high-pulse energy, achieving brief duration of contact of the components and low temperature of fiber composite material manufacture. As the experiments showed, increasing the speed of loading of the blank with constant remaining compacting parameters yielded the

best mechanical properties with flow in the space between fibers equal to 0.7-1.0 fiber diameter. In order to optimize short-term and long-term strength, the fiber composite specimens were heat treated after manufacture.

Proper selection of the process of fiber composite manufacture only partially solves the problem of compatibility of fibers and matrix. During use, particularly at high temperatures, one must consider the type of physical-chemical interaction of the components. The best results from the standpoint of thermodynamic compatibility of the fiber and matrix components are achieved by the formation of a diffusion zone consisting of solid solutions. Even an increase in zone thickness to 20-25 μm does not significantly decrease the properties of the fiber composite material.

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INFLUENCE OF PHYSICAL-CHEMICAL REACTION BETWEEN REINFORCING ELEMENT AND MATRIX IN GAS-THERMAL SPRAYING ON MECHANICAL PROPERTIES OF REINFORCING ELEMENTS

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Particular attention has been given in recent studies of composite materials to the interface between the strengthening reinforcement and the matrix, since the state of this interface largely determines the mechanical properties of the material. The method of gas-thermal spraying has been successfully used to manufacture composite semifinished goods strengthened by continuous fibers of boron, carbon and silicon carbide. This method allows the interaction of the matrix with the reinforcement to be varied widely by changing the temperature of the matrix as it is applied and the temperature to which the reinforcement is heated.

This work studies the influence of thermal activation of thin films of the alloys used as reinforcement on the physical-chemical interaction of the reinforcement with the aluminum matrix and the influence of this interaction on the matrix-reinforcement bond strength. The matrix was technically pure AD1 aluminum wire 1.1 mm in diameter. The reinforcement was strips of alloys based on iron and nickel, alloyed with metals or metalloids, with a thickness of 25-50 μm, width 1.0-1.5 mm. Spraying was performed on a type UPU-Zd installation. The plasma-forming gas was argon. The temperature of the strip was varied between 20 and 250 °C to vary the degree of reaction between the aluminum and the strip. The temperature of the strip was monitored by a chromel-aluminum thermocouple. The strip was then pulled away from the matrix to study the physical and chemical interaction between the matrix and reinforcement. A scanning electron microscope was used to perform planometric measurements of the matrix residue on the surface of the strip. It was assumed that the matrix residue on the strip represented foci of the interaction occurring during spraying. The tests indicated that the bond strength of these spots with the strip was equal to the strength of the matrix. The results of measurements performed at these foci are presented in the figures in relative units as a function of strip temperature before spraying.

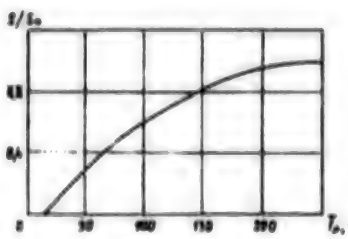

Figure 1. Area of Interaction at Aluminum-Strip Interface As a Function of Temperature.

$\sigma(T_s)/\sigma_s$, %
T_s, °C

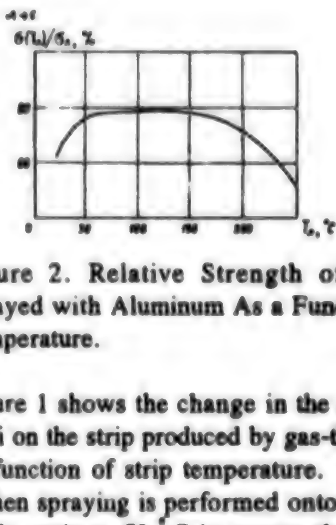

Figure 2. Relative Strength of Strip Sprayed with Aluminum As a Function of Temperature.

Figure 1 shows the change in the area of interaction foci on the strip produced by gas-thermal spraying as a function of strip temperature. No reaction occurs when spraying is performed onto a cold strip. Heating the strip to 50 °C increases the area of the interaction foci slightly. As the strip temperature increases, the interaction foci increase in area. Interaction over the full surface of the strip occurs at 250 °C. Increasing the temperature of the strip at which spraying is performed to 150 °C increases the density of the interaction foci to 0.7, without decreasing the strength of the strip (Figure 2). Heating to 200 °C increases the area of the interaction foci to 0.86, but decreases the strength of the strip by 14%. Increasing

the temperature to 250 °C increases the density of interaction foci still further, to 0.94. In order to determine the type of bond between the aluminum matrix and the strip, the material was annealed at 600 °C for 0.25 to 6.0 hours. Intermetallides were found on the surface of the strip after annealing for the shortest period of time tested, and further increases in annealing time did not change the area occupied by the intermetallides. No intermetallides were found after spraying onto a cold strip (Ts = 20 °C), the area of the intermetallides increasing with increasing temperature of the strip. The area occupied by intermetallides on the strips after annealing was equal to the area of the interaction foci. Consequently, there was physical contact between the strip and the matrix during the spraying stage in the interaction foci, but the interaction did not cause the formation of intermetallides, decreasing the strength of the trip.

Gas-thermal spraying allows the bond strength between the strip and the aluminum matrix to be varied broadly without significantly changing the mechanical properties. The optimal condition for producing a strong bond between the strip and the aluminum matrix is heating of the strip. As strip temperature increases, bond strength increases until it reaches the strength of the aluminum matrix and failure occurs through the matrix.

620.22-419

OPTIMIZATION OF POWDER COMPOSITE MATERIAL ROLLING PROCESS

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The processes involved in compacting composite materials with a powder matrix and knitted screen reinforcement have practically never been studied. To achieve the maximum possible compacting, it is important to determine the variation in density of such composite materials as a function of reinforcing screen structure and rolling direction.

This work, based on a solution suggested earlier by the authors to the problem of rolling a thin layer of a compacting orthotropic material1, studies the problem of optimizing the process of joint rolling of a metal powder and a knitted metal screen. The equation defining the distribution of relative density over the length of the deformation focus in the backward slip zone, where compacting occurs2 is:

$$\frac{d\tau}{\tau} = \frac{\alpha\, d\rho}{\rho(\beta-\alpha)} \qquad (1)$$

here τ is the polar radius, ρ is the relative density, α and β are functions of the relative density ρ included in the creep condition.

The relationship between α and β

$$\frac{\beta}{\alpha} = \frac{(1+\rho)^{0,5} - 2\sqrt{3}\,(1-\rho)^{0,5}}{k\,(1+\rho)^{0,5}} \qquad (2)$$

includes k — the ratio of the limits of creep in uniaxial compression in the direction of rolling and in the direction perpendicular to the rolling plane. When a powder reinforced blank is compacted as it moves through the deformation focus it is necessary that $\frac{de}{d\rho} < 0$ This requires the following condition, obtained from (1) considering (2):

$$k > 1 - \frac{2\sqrt{3}\,(1-\rho)^{0,5}}{(1+\rho)^{0,5}} \qquad (3)$$

Equation (3) shows that the maximum possible density ρ^* with k % 1 is determined by the expression

$$\rho^* = \frac{12-(1-k)^2}{12+(1-k)^2} \qquad (4)$$

while where $k \geq 1$ we have $\rho^* = 1$.

Representing (1) considering (2) as

$$\frac{d\rho}{d\tau} = \frac{\rho}{\tau}\left\{ \frac{1}{k}\left[\frac{(1+\rho)^{0,5} - 2\sqrt{3}\,(1-\rho)^{0,5}}{(1+\rho)^{0,5}} \right.\right. \qquad (5)$$

we can conclude that in order to produce the highest possible density it is necessary to strive to increase the value of k. To achieve a high value of k, we must consider the anisotropy of the properties contributed to the composite material by the structure of the reinforcing screen. This results from the difference in the density of placement of loops in the direction of the columns and rows of loops. Knowing the ratio of the yield point of the composite material in these directions, we can, considering (5), conclude that if n & 1, in order to achieve greater density the material should be rolled parallel to the columns, while otherwise it should be rolled parallel to the rows. If n = 1, both rolling directions are effective.

The ratio of yield point can be computed from the expression for potential deformation energy for an orthotropic material, using the principle of Beltrami.

Our calculations have shown that

$$n = \left(\frac{E_x}{E_y}\right)^{0,5}$$

where Ex and Ey are the effective elasticity moduli of the reinforcing screen in the major directions x, corresponding to the direction of the loop columns and y, corresponding to the direction of the loop rows.

The effective elasticity moduli of the screen depend on changes in loop shape under the influence of loading.

For example, in a "rib-knit" screen the shape of a loop can be described by the expression

$$\theta = \arcsin\left(A\frac{\pi}{2a}\cos\frac{\pi}{2}\frac{s}{a}\right) \qquad (6)$$

where θ is the slope angle of a tangent to the flexible loop line; A is the amplitude representing the extension of the loop; a is a parameter representing the length of a loop Su equal to 1/4 S.

The effective elasticity moduli of this screen Ex and Ey can be calculated as functions of parameters A and a, determined experimentally by stretching the screen. These data are used to construct a curve for

which n = 1 on a graph of a as a function of A. This curve determines the geometry of the screen for which the directions of rolling are equivalent. In the area where n & 1, as defined by this curve, it is best to roll parallel to the loop columns, in the other area it is best to roll parallel to the rows.

If the rolling direction is known, then we can select as k the value kx = $(Ex/E_y)^{0.5}$ or ky = (Ex/Ey)0.5, in which the value of Ez is defined as the elasticity modulus of the matrix material at the corresponding matrix powder density.

Thus, in the rolling direction which has been selected the optimal geometric parameters of the knitted screen are those which provide the maximum rigidity in that direction.

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UDC 539.3:519

STUDY AND DEVELOPMENT OF DIFFUSION BONDING OF TITANIUM WITH CERAMIC

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Ceramics have a number of advantages over other materials: excellent refractory qualities, low density, great hardness and corrosion resistance. However, ceramic materials also have a number of shortcomings, the most important of which is their brittleness. The advantages of ceramics can be effectively used, and their disadvantages somewhat compensated, by the creation of composite structures with metals and alloys.

Composite materials containing ceramics can be produced by solid-state joining methods, particularly diffusion welding, allowing the processes occurring at the interface between the dissimilar materials to be controlled to some extent, assuring a good bond. This work presents the results of studies and development of a technology for diffusion joining of VK94-1 high-alumina ceramic with VT20 titanium alloy for the manufacture of titanium-ceramic facing-type products.

It has been established that the formation of a vacuum-tight joint between these materials at 1473-1523 K is accompanied by intensive recrystallization effects, which change the structure and mechanical properties of the titanium alloy. A search has been undertaken for an intermediate lining material to support the creation of a high-quality titanium-ceramic joint at bonding temperatures suitable for titanium, $T_b \leq 1123$ K. Positive results have been obtained by the use of a combined interlayer of aluminum and magnesium or magnesium-containing aluminum alloy AMg3, AMg6, AMts, et cetera. The quality of the joint produced depends on the structure and phase composition of the surfaces, which are determined by the parameters of the diffusion welding process: temperature, compressive force and welding time. The temperature and time of interaction at the titanium-aluminum-aluminum alloy-ceramic interface must be sufficient to achieve strong adhesion bonding among the material components, but must be limited by the intensive reactions which may occur, leading to the formation of brittle intermediate layers decreasing the strength of the metal-ceramic joint.

The influence of the structure of the transition layers (layer bond strength) was evaluated from the results of metallographic and x-ray microscopic analysis as well as changes in the strength characteristics of the joints. The data of metallographic studies indicate good quality of titanium-ceramic joints obtained by the use of intermediate layers of aluminum and aluminum alloys. Pores, cold welds, cracks and other welding defects were absent in the contact zone, the phase interface was sharp, without a visible transition zone. Inseparable joints between titanium and aluminum are formed by the formation of a solid solution of aluminum in titanium. When the maximum solubility in the titanium-aluminum system is exceeded, an intermediate phase is formed, the thickness of which increases with increasing holding time and temperature. The results of microhardness measurements indicate that the hardness of the new phase matches that of the intermetallic compound $TiAl_3$. A layer of intermetallide up to 8 μm thick does not decrease the strength of the joint produced.

A solid-phase joint between the ceramic and AMg6 alloy is formed by chemical reactions between the materials and by diffusion of magnesium into the ceramic and silicon into the AMg6 alloy. These elements diffuse along the grain boundaries of the aluminum in the AMg6 and the grinds of aluminum oxide in the ceramic.

The studies performed indicated the optimal welding conditions: welding temperature $873 + 10$ K, compressive force 8-10 MPa, isothermal holding 30 minutes. The optimal welding modes were used to manufacture titanium-ceramic units and parts, joints between ceramic plates and cylinders and titanium alloy specimens 0.5 to 10 mm thick. Titanium-ceramic layer specimens measuring 120×120 mm both compensated and uncompensated.

539.3.519

DESIGN OF METAL-CERAMIC FEMALE CLAMPING UNITS

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Structural materials based on ceramics, glasses and pyrocerams are increasingly widely used, as a result of their good mechanical strength at high temperatures in various media, their vacuum tightness, thermal stability and radiation resistance.

In addition to the development of new structural materials, it is also necessary to produce metal-glass, metal-ceramic units with superior usage characteristics. Since ceramic materials have a number of specific properties (such as brittleness, low tensile and flexural strength), it is not always possible to use traditional methods to join parts made of these materials.

Diffusion welding is one of the most promising methods of producing good joints in glass-glass, glass-metal, ceramic-metal and other composites.

Two types of joints obtained by diffusion welding are distinguished: in a plane — edge joints, on surfaces — male, female (with respect to the nonmetallic part). Edge joints are frequently used in the manufacture of metal-ceramic units. The second type is less common, which, in our opinion, results from the absence of methods to design male/female joints, as described below.

One specific feature of a metal-ceramic unit with a male/female joint is that the ceramic part is always the male part. This is because of the high compressive strength of the ceramic. The female part must be made of a material with a clearly expressed yield area, which is characteristic of plastic metals (such as Al and its alloys).

To produce a joint, the parts are heated to the welding point and the ceramic part is pressed into the metal part. The metal part may be reinforced with a ring. The joint is held at the welding temperature for some time then slowly cooled to relieve residual stresses due to the decrease in the temperature gradient in the ceramic part, and the process of stress relaxation in the joint zone.

The pressing which occurs in the process of manufacturing these joints makes them noncritical in terms of the medium in which the joint is formed. The process need not be performed in a vacuum, but can be performed in air, making it significantly simpler. This is because the pressing of the hard ceramic part causes mechanical removal of the oxide film from the inner surface of the metal part, which is necessary for the formation of the joint. If pressing is not used, preliminary chemical treatment of the metal part is required and an oxygen-free medium must be maintained in the area of the joint.

Thus, male/female joints made on a cylindrical surface can be obtained if the parts of the metal-ceramic unit have dimensions providing an interference (negative difference in diameters of surfaces to be joined), causing a certain contact pressure between the welded surfaces at the welding temperature. The optimal metal-ceramic unit geometry meets the following conditions:

- satisfies the condition of ceramic part strength at the welding temperature under normal conditions;
- provides the necessary contact pressure;
- retains load-bearing capacity of metal part and ring.

The maximum pressures at which the ceramic part is not damaged can be determined from the maximum equivalent stress, calculated by the method of initial parameters for thickwall cylinders.

The design of the metal part and ring is based on the theory of small elastic-plastic deformations. The following assumptions are made to determine the geometry of the metal-ceramic unit:

- applicability of theories and methods used;
- residual axial stresses arising due to the difference in the coefficient of thermal expansion of the ceramic and metal parts are ignored;
- uniform distribution of pressure in the contact zone.

The method of designing male/female joints has been implemented in a software package for the YeS computers (in FORTRAN) and minicomputers (in FOCAL).

UDC 539.3:519

DIFFUSION JOINING OF TUNGSTEN-FREE HARD ALLOYS WITH STEEL FOR TOOL MANUFACTURE

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Tungsten carbide plays a leading role in the manufacture of hard alloys. However, the increasing shortage of tungsten and cobalt have stimulated intensive development of tool materials not containing tungsten, using refractory compounds of titanium (carbides, carbonitrides, nitrides) with various binders. Hard alloys based on refractory titanium compounds are referred to as tungsten-free hard alloys.

Tungsten-free hard alloys are distinguished by their great wear resistance, low coefficient of friction, reduced adhesion with materials being worked and by the fact that their density is slightly more than half that of tungsten-containing alloys, as well as their good strength characteristics.

Thanks to these properties, tungsten-free hard alloys can successfully be used to replace standard hard alloys in such operations as turning, milling, and they are also used in the manufacture of measuring instruments, rapid-wearing parts, drawing and bending dies.

Due to their high cost and low tensile and flexural strength, tungsten-free hard alloys should be used as inserts, joined by some method to steel tool bodies.

This work studies the specifics of diffusion joining of tungsten-free hard alloys containing tungsten carbide with a steel binder (carbide steels) and with a nickel-molybdenum binder (type TN-20) to steels used in the manufacture of composite tools.

It has been found that the strength of diffusion bonding of carbide steels with other steels depends not only on the welding conditions, but also on the content of titanium carbide in the alloy and the alloying of the steel binder. Mechanical testing of welded joints between TiC carbide steels and type U8 steel with various contents of titanium carbide (10, 20, 30, 40% by mass) has shown that changing the titanium-carbide content from 10 to 40% decreases the bond strength by almost half.

The bond strength can be increased without changing the titanium-carbide content by increasing the alloying of the metal binder. The studies showed that carbide steels containing alloy binder such as 5Kh6VM2, Kh6VM3 and 6Kh3M3D have significantly better bond strength with U8 than do carbide steels.

X-ray microspectral studies performed with a "Camebax" microprobe showed that redistribution of the alloying elements occurs in the area of the joint, the width of the diffusion zone being 20-25 μm. The less titanium carbide in the carbide steel, the wider the area of diffusion interaction.

It was also found that in heat-treated carbide steels (up to 50% TiC_{tot}) the process of diffusion welding can be combined with heat treatment of the welded specimens (hardening, annealing). Tungsten-free hard alloy type TN20, in which the molybdenum-nickel binder has higher activation energy, has less tendency to seizing with metals during diffusion joining. This requires the use of activating interlayers of various types, to facilitate the development of diffusion processes in the joint zone. X-ray microspectral studies showed that an intermediate layer of nickel caused more intensive reaction among the iron, nickel and titanium elements at the steel-nickel interlayer boundary. When intermediate layers of ultradispersed nickel powder were used, redistribution of elements occurred throughout the entire thickness of the intermediate layer due to the increased diffusion activity of the sintering powder, which had a well developed surface. The best results were obtained by a combined layer of metallic and powdered nickel, in which diffusion processes were more intensive and the components were smoothly distributed. During welding, the nickel layer is replaced by an alloy based on nickel and iron with greater hardness and a reduced concentration gradient of alloying elements, with additive mechanical properties, leading to an increase in the welded joint strength.

These specifics of diffusion joining of tungsten-free hard alloys with steels allowed us to develop process recommendations for the manufacture of composite products and tools with the cutting portion made of tungsten-free hard alloys.

UDC 539.3:519

COMPENSATION OF RESIDUAL THERMAL STRESSES IN DIFFUSION WELDING WITH MULTILAYER INSERTS

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The manufacture of products with predetermined physical-mechanical and heat-physical properties can be performed by diffusion welding of dissimilar plates. The joints produced usually involve various intermediate layers of metal materials and are made at temperatures of several hundred degrees, in some cases over 1000 °C. As the joints cool to room temperature, significant thermal stresses may arise in the dissimilar plates, greatly influencing joint strength. However, by selecting the material and plate thickness, it is possible in principle to optimize the thermal stresses in the product. It is particularly important to decrease the maximum tensile stresses in layers of ceramic materials, since the ceramic materials have low tensile strength. The stress state of these products was studied experimentally and by mathematical modeling. The object of the study was cylindrical specimens of various diameter made of UF-46 ceramic and stainless steel. The diffusion welding was performed through copper interlayers of various thicknesses, as well as multilayer dissimilar metal interlayers. It was found that the most suitable material for the thermal compensating layer (thermocompensator) was niobium. The method of finite elements was used for an initial computer determination of the thickness of the niobium interlayer (thermocompensator) to reduce the maximum tensile stresses. The problem was analyzed both in the elastic area and in the area of slight elastic-plastic deformations. The selected compensator thickness was then used for experimental welding and strength testing. It was found that product strength was increased by the use of the optimal thickness.

UDC 539.3:519

DETERMINATION OF RESIDUAL THERMAL DEFORMATION IN MULTILAYER PLATE PRODUCTS BY HOLOGRAPHIC INTERFEROMETRY

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When plates of different materials are permanently joined by diffusion welding, significant residual stresses usually arise. These stresses can be determined from the movement and deformation of the external surfaces they cause.

This work studies the possibility of determining residual strains and stresses in products with near-planar stress state by holographic interferometry in combination with the numerical methods of finite elements and methods of the theory of thin rigid inflexible plates. Mathematical modeling was performed both in the area of elastic stresses and strains and in the area of slight elastic-plastic deformations. Experiments were performed on cylindrical specimens of UF-46 ceramic, to one end of which plates of various metals were bonded by diffusion welding.

The analysis indicated that the combination of holographic interferometry with methods of the mechanics of deformed bodies yielded a reliable picture of the stress state in plate products welded by diffusion welding, and allowed estimation of the accuracy of the results obtained.

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UDC 620.198.43:669.71'782'784

INFLUENCE OF HEAT TREATMENT ON INTERACTIONS IN ALUMINUM-BORON COMPOSITE

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Composite materials with metal matrices are primarily used for high temperature work. Under these conditions, the thermal stability of the interfaces is of decisive significance in terms of operational reliability of a metal composite.

The development of chemical reactions at the phase interface between a boron fiber and aluminum alloys was studied. Studies were performed on boron fibers 140 μm in diameter. Metallization was performed with aluminum (Al) and its experimental alloys with surface-active additives of bismuth (5.1 wt. %) and antimony (5.9 wt. %). Metallization was performed by drawing the fiber through a melt, as described in [1]. The thickness of the metal coating on the boron fibers was 2 μm. The quality of the coating and its continuity were evaluated by means of a Neophot-2 optical microscope. The strength of the initial and aluminized fibers was determined with an Instron tensile-testing machine. The strength of the boron fibers with B/Al, B/Al-Sb and B/Al-Bi fibers was 0.9, 1.08 and 1.1 times the strength of the initial boron fibers. X-ray diffraction and electronographic methods were used to determine that the phase interface of the boron-aluminum system consisted of a solid solution of boron in aluminum Al(B) and the compounds AlB_2 and AlB122. Alloying of the aluminum matrix with bismuth and antimony did not change the phase composition of the phase interface, but the number of seed centers of the interaction products decreased.

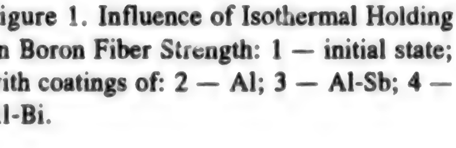

Figure 1. Influence of Isothermal Holding on Boron Fiber Strength: 1 — initial state; with coatings of: 2 — Al; 3 — Al-Sb; 4 — Al-Bi.

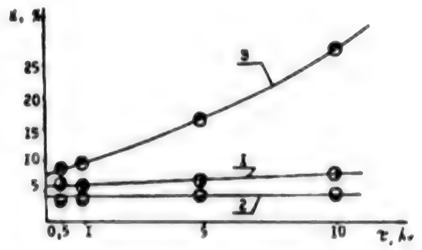

Figure 2. Influence of Isothermal Holding on Interaction Products in Systems: 1 — B/Al-Sb; 2 — B/Al-Bi; 3 — B/Al.

Fibers of boron and boron with coatings of Al, AL-Sb, Al-Bi were annealed in air at 573 K, 673 K, 773 K for 0.5, 1.0 and 10.0 hours. The boron fibers did not lose their strength after annealing at up to 673 K, but further increases in temperature greatly reduced the strength of the fiber due to oxidation. Boron fibers with aluminum coatings lost 20% of the strength of the initial fiber when heat treated at 773 K for 0.5 hours. Boron fibers coated with Al-Sb and Al-Bi coatings did not lose strength at this temperature throughout the entire interval tested (Figure 1).

The segregation of surface-active additives in an aluminum coating was studied on a type JSM-U3 scanning electron microscope using transverse sections of metallized fibers[3]. The metallographic studies and planometric methods of counting the reaction products on the surface of the fiber after dissolution of the aluminum coating in 10% KOH showed that the growth of the boride phases on the phase interface between fiber and matrix in the B/Al-Bi and B/Al-Sb systems was very slow in comparison to B/Al (Figure 2), a result of the segregation of alloying additives at the phase interface, creating a "barrier" to the development of chemical reactions between boron and aluminum during heat treatment.

Thus, coatings of Al-Bi and Al-Sb improved the thermal stability of boron fibers.

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UDC 621.763(088.8)

PROTECTIVE COATINGS ON REINFORCING PHASE IN DESIGN OF COMPOSITE MATERIALS

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Modern technology has developed high-strength fibers with relatively little area. Thus, there has been intensive study in Japan of the manufacture of coreless fibers of silicon carbide, boron, oxides of zirconium, titanium and aluminum[1]. They are distinguished by their high strength (up to 6000 MPa) and low density. These parameters remain practically constant at temperatures from zero to 770 K. Similar fibers have been developed, studied and used in the USA and FRG for the creation of new composite reinforced materials based on metal, ceramic and polymer matrices. In addition to these fibers, traditional metallic fibers of tungsten, molybdenum, niobium and their alloys are widely used, as well as ceramic fibers of boron, silicon and zirconium carbides obtained by precipitation from the gas phase onto a tungsten core.

In most cases the technology of manufacture of composites involves heating of pieces to rather high temperatures, resulting in undesirable chemical processes at the fiber-matrix phase interface, eliminating the effect of reinforcement. The process of degradation of the reinforcing phase can be eliminated or retarded by the use of protective layers of refractory compounds such as carbides, nitrides or oxides. Naturally, the introduction of additional layers to a composite complicates the system, resulting in the appearance of new interfaces. Nevertheless, protective barrier coatings do provide stability of phase interfaces for a certain period of time at high temperatures.

The Institute of Mechanics Problems, Ukrainian Academy of Sciences has developed new barrier oxide coatings 1-10 μm thick for metal and ceramic reinforcing fibers (tungsten, molybdenum, silicon carbide, boron, et cetera). The process of application of the protective layers which is used is quite simple, economical and can be easily included in any process chain for fiber production.

This article presents a study of the influence of oxide coatings on the tensile strength of fibers. Figure 1 shows characteristic curves of the strength of the boron, silicon carbide, tungsten and molybdenum fibers as functions of coating thickness. As we can see from the graph, with coating thicknesses of up to 2-3 μm the strength of the fibers is retained approximately at the initial level, and in some cases even increases, as is the case for boron filaments.

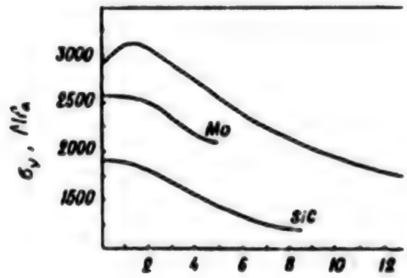

Figure 1. Reinforcing Fiber Strength As a Function of Coating Thickness

Weibull statistical processing of the results of testing brittle boron and silicon carbide fibers indicated that the distribution of initial filament strengths showed significant variation of values with a high variation factor.

However, this variation factor decreases for fibers with oxide coatings and the distribution of strength becomes more uniform. This, in our opinion, results from the ordering of the structure of the fiber as the coatings are applied.

The metallographic studies performed and the study of the specifics of the failure of ceramic and metal fibers indicated that the coatings developed have two layers. The lower layer, directly adjacent to the fiber surface, is rather strongly bonded to the base, while the upper layer is looser and characteristically has microscopic cracks.

Fractographic analysis showed that deformation of a fiber causes multiple cracking of the coating. The cracks in the surface oxide layer gradually extend into the coating, causing delamination and relaxation of stresses in the fiber itself.

This work presents the results of investigation of the reaction between phases in composite materials based on aluminum, titanium and nickel-chromium matrices reinforced with continuous fibers having pro-

tective oxide layers. It is shown that the use of barrier coatings of refractory oxides can increase the temperature-time life of reinforced composites and improve their strength properties at high temperatures.

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UDC 669.018

USE OF FRACTURE MECHANICS METHODS TO CERTIFY COMPOSITE CERAMIC-METAL MATERIALS

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Composite materials in ceramic-metal systems (cermets), combining the positive properties of their components, are promising for high-temperature applications in many branches of industry[1,2]. However, in spite of the high level of strength which has been achieved, cermets are usually brittle and products made of them do not have the necessary operational reliability.

At present, the fracture resistance of brittle materials is usually evaluated by the K_{Ic} criterion — the coefficient of stress intensity at equilibrium in a body with a crack. The value of K_{Ic} does not always correlate with the behavior of brittle materials under usage conditions, e.g., where temperatures change rapidly[3]. Consequently, single-parameter certification of many brittle materials is not sufficient. As a result of various dissipative processes involved in fracture (microscopic cracking, reorientation and branching of cracks, plastic deformation of the metal component), subcritical crack growth may occur in cermets under active loading, and their crack resistance must by a multiple-parameter characteristic, utilizing the entire R-curve of crack propagation resistance, or by the use of an energy criterion such as the specific work of fracture γ_F.

In order to develop a methodologic approach to the certification of ceramic-metal materials, an analytic description of R-curves has been obtained by the use of model concepts of the dissipative zone in advance of the tip of a major crack in the loading process, as was done in [4] for the fracture of elastic-plastic materials. In the analysis of the energy balance of a body with a crack, various dissipative processes which can occur during the fracture of cermets were analyzed. It was found that there is a "universal" R-curve of the resistance to crack propagation for all of these processes. The variation of the increment in a crack Δl as a function of the change ΔK_I of the stress intensity coefficient in the subcritical stage is described by the equation

$$\Delta l = \beta(\Delta K_I/I_{Ic})^2,$$

where β is a function of the properties of the cermet's structural components. The coefficient β, in combination with K_{Ic}, defines the energy consumption of the fracture of a brittle material.

Experimental studies were performed of subcritical crack growth in lanthanum chromite-chromium and aluminum oxide-chromium cermets as a function of manufacturing conditions, ratio of components and structure. For lanthanum chromite-chromium cermets it was found that the transition from a sintering technology to high-speed pressing increased the duration of the subcritical crack growth stage and the energy consumption of fracture. Aluminum oxide-chromium cermets with homogeneous distribution of the dispersed metal phase required less energy to fracture than did cermets with layered-granular structure. The subcritical crack growth in the latter resulted from reorientation of a major crack propagating along the boundaries of the layers in the material. Reorientation involved a change in local stress intensity factor and resulted in processes of periodic acceleration and inhibition of crack growth.

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UDC 620.178:669.018 45:621 762 5: 621.81

INFLUENCE OF CERTAIN ADDITIVES ON STRUCTURE AND MECHANICAL STRENGTH OF TITANIUM NITRIDE-NICKEL METAL CERAMIC MATERIALS

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Due to the good corrosion and heat resistance of TiN-Ni cermets, these materials are used in elements which must operate at high temperatures in corrosive media. However, these materials have insufficient strength, hindering their practical application.

In this work, we studied the influence of Mo, C and Cr additives on the structure, strength and modulus of elasticity of TiN-Ni cermets. The basic material studied was TiN = 30 vol.% Ni, which had the maximum strength in this system after sintering of the optimal structure and phase composition (σ_u = 800 MPa).

It was found that the addition of about 9% Mo to the metal binder of the material, while preserving the total binder content of 30 vol.% and identical porosity, had practically no influence on the strength level of the sintered material. However, in order to achieve identical values of porosity and strength of the material with the addition of Mo it was necessary to perform sintering at 100 °C cooler than when molybdenum was not used. Increasing the sintering temperature of specimens with the nickel-molybdenum binder by 100° over the optimal temperature increased the porosity of specimens, causing growth of the titanium nitride grains (from 12 to 15 μm), changing the phase composition of the binder and, as a result, decreasing its strength by 14%. TiN grain growth was greater in an Ni + Mo binder than in pure nickel, as a result of the decrease in the temperature at which the liquid phase appears during sintering, facilitating grain growth by the mechanism of coalescence and recrystallization through the melt.

The addition to the metal nickel binder of 5% Cr significantly deactivates the shrinkage of specimens in comparison to the Mo additive. The maximum compacting in this case is achieved at a temperature of about 250 °C higher than when molybdenum is added. The maximum strength of the TiN + 30 vol.% (Ni + 5% Cr) is virtually the same as the strength of the base material. The method of x-ray phase analysis revealed that the metal binder contained titanium intermetallides (Ni_3Ti and traces of Ti_2Ni and $TiCr_2$). Since the addition of chromium requires higher sintering temperatures, increasing the titanium nitride grain size and causing intensive segregation of intermetallides on the phase interfaces, this is the major reason for ineffectiveness of the addition of chromium in an attempt to increase the strength of the material. The highest strength level is that of the metal ceramic material TiN + 30 vol.% Ni with the addition of 3% C after sintering with uniform and continuous heating. This creates the minimum porosity (about 5%), yielding a relatively fine-grained structure with the optimal phase composition (TiCN, Ni, Ni3Ti), while increasing the time, and particularly the temperature, of sintering causes some decrease in porosity, the appearance of brittle phases and an increase in the size of solid phase grains. Thus, whereas after uniform and continuous heating the phase composition of the metal binder contained only a nickel-based solid solution and the nickel-rich intermetallide Ni_3Ti, which yielded high strength (σ_u = *1020 ±50 MPa), after isothermal sintering at a higher temperature (30° higher) the strength decreased by 32% (to σu = 700 ±20 MPa) due to the formation of a titanium-rich intermetallide (Ti2Ni) and a decrease in the fraction of the Ni solid solution and Ni3Ti, in spite of the fact that the total content of the metal phase in the specimen increases by 5-10% due to the transition of titanium from titanium nitride to nickel. Fractographic studies of bend-test specimens showed that regardless of the additives used, the metallic binder fractures by spalling (quasispalling), while the fracture of the titanium nitride grains is mixed (intercrystalline-transcrystalline) in nature. The ratio of transcrystalline to intercrystalline fracture and the strengths of the material depend on the phase composition of the binder, which is related to the temperature and time of sintering of the specimens. In particular, it has been established that an increase in the content of the more molybdenum-rich intermetallide (Ni_3Mo) in the binder with a decrease in the concentration of the nickel-rich intermetallide (Ni_4Mo) significantly decreases the amount of transcrystalline fracture of the solid phase and the strength of the specimens with the nickel-molybdenum binder.*

Studies of the influence of phase composition of sintered materials in the system TiN + 30 vol.% Ni with additives on elasticity modulus showed that it is primarily influenced by the porosity of the material.

primarily influenced by the porosity of the material. This characteristic is less sensitive to the phase composition of the material. The introduction of various additives to the material of the basic composition has practically no influence on elasticity modulus.

UDC 620.178:621.762.5:669.018.45:621.81

INFLUENCE OF PROCESS PARAMETERS AND Ni-Mo RATIO ON STRUCTURE AND MECHANICAL STRENGTH OF METAL-CERAMIC MATERIALS IN THE SYSTEM TiN-TiC-NbC-(Ni-Mo)

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Metal-ceramic materials have a number of properties not found in multiphase materials based on refractory compounds. Materials based on TiC have been long and widely used as strong machine-building materials, the best binder for which is nickel-molybdenum, which provides superior mechanical characteristics. However, these materials do not have sufficient toughness and crack resistance.

These shortcomings are partially compensated in materials containing titanium nitride. This work is dedicated to the stud, of the influence of process parameters involved in the sintering of TiC + TiN + Ni + Mo on the structure of the materials produced, their phase composition and bending strength, as well as investigation of the promise of adding niobium carbide NbC to these materials.

The materials studied had identical content of nickel-molybdenum binder, but the ratio between nickel and molybdenum varied in the range Mo:Ni = 1:1, 1:1.5, 1:4.

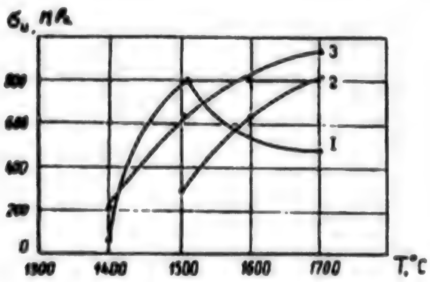

Figure. Change in Bending Strength As a Function of Sintering Temperature of Specimens with Mo:Ni Ratio 1 — 1:1; 2 — 1:1.5; 3 — 1:4

As we can see from the graph (cf. figure), the strength of the specimens after sintering by uniform and continuous heating to 1400 °C was approximately the same regardless of the ratio between Ni and Mo. Increasing the sintering temperature to 1500 °C significantly increased the strength of the material where the Mo:Ni ratio in the binder was 1:1 (σ_{Iu} from 50 to 830 MPa). With an Mo:Ni ratio of 1:1.5, the increase in strength was more gradual, reaching the same value only after sintering at 1700 °C. The change in strength of the specimens achieved by the use of a nickel-rich binder (Mo:Ni = 1:4) with sintering temperature was intermediate in nature, with the maximum strength reached after sintering it 1600 °C.

We should note that increasing the sintering temperature of specimens with Mo:Ni = 1:1 to 1600-1700 °C significantly decreases strength (from 830 to 450 MPa).

This change in strength can be explained as follows: with a ratio of metal components in the binder of 1:1, the composition of the binder is near utectic and it wets the solid-phase framework quite well, as is confirmed by the high degree of compacting of these materials at 1500 °C, increasing very little with further increasing in sintering temperature. The good wetability supports high strength of the interface between particles, while the utectic nature of the binder assures good plasticity under load. A change in the ratio of nickel to molybdenum in favor of nickel results in a reduction in wetability and sintering capacity, restoration of which requires an increase in the sintering temperature.

However, increasing the sintering temperature also increases the chemical reactions occurring at the phase interface, and also in the TiN-TiC solid phase. In particular, more intensive dissolution of titanium in the nickel-molybdenum binder occurs, with greater exchange of metalloid atoms between TiN and TiC, dissolution of nickel and molybdenum in the titanium carbide and nitride. Each of these processes has some influence on the strength of the material as a whole. However, as we can see from the graph, further increases in sintering temperature above the optimal temperature lead to segregation of excess intermetallides during cooling, reducing the strength of the particle interfaces, and also causing significant growth in the size of the TiN and TiC grains. As a result of all this, the material loses strength.

Studies of fractograms of bend-test specimens established that all of the specimens had primarily transcrystalline brittle fracture. The crack usually

traveled through the metal binder. This means that in the specimens studied there was a strong interphase (adhesion) bond, stronger than the cohesion single-phase bond.

In all of the compositions studied the content of niobium carbide was the same — 3%. This content of NbC is optimal from the standpoint of producing a fine-grain material structure. The NbC on the grain boundaries significantly inhibits the growth of titanium carbide and nitride grains which, as we know, has a positive influence on the strength of the material. As sintering time increases, NbC does not inhibit shrinkage, which is a technological advantage.

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PROSPECTIVE APPLICATION OF ULTRADISPERSED MATERIALS TO HARDEN PRECISION SURFACES OF HYDROPNEUMO LUBRICATION EQUIPMENT PARTS

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An important characteristic for the precision surfaces of parts in hydropneumo lubrication equipment, testing and measurement systems, cutting (drilling, countersinking, tapping, milling, et cetera) and pressing tools is the time of retention of accuracy.

It is emphasized in the recommendations for introduction of CEMA standard 144-75 and CEMA standard 144-75 that increasing wear life is just as important as improving initial quality of a material or strengthening the material to increase the wear resistance of parts.

In contrast to cutting processes, the application of new material by coating methods is more universal and effective from the standpoint of assuring the required physical and mechanical properties of a surface layer[1].

On the example of estimating the accuracy of the dimensions of parts in contact (seating size 20 mm; coating thickness 30 μm), let us study the capabilities of three methods of applying coatings: thermal vacuum spraying, electrical explosion of wires and galvanic application of coatings (providing dimensional accuracy of 6, 9, and 3 μm, respectively). Thus, application of coatings achieves an accuracy corresponding to quality class 5 by electrical wire explosion, class 4 by thermal vacuum spraying, and class 2-3 by galvanic application of coatings, i.e., the best results can be obtained by the electrochemical method.

The results of the studies involving application of a composite electrochemical coating (based on chromium and ultradispersed diamond) showed that the problem of wear of heavily loaded units (engine cylinders, crankshafts) can be helped by these coatings: with thicknesses of 15-500 μm, serviceability can be improved by a factor of 2 to 3.

An ordinary cutting tool coated by chrome plating with ultradispersed diamond (clusters) has a low coefficient of friction and good wear resistance. The increase in service life of tools is as follows: drills for metal 1.58 times, for glass and plastic 10-30 times; countersinks — for metal 2-5 times, for glass and plastic 50 times; taps — for metal 4-5 times; milling cutters — for metal 2.4 times. The increase in the service life of pressed tools for cold drawing of metals is 2.5-4 times, press tools for powder metallurgy — more than 90 times. The increase in microhardness of the coatings is by 1.5-2.5 times 2.

Studies were performed of the application to precision surface parts of coatings: based on chromium and ultradispersed nichrome; based on copper and ultradispersed diamond. New wear-resistant coatings were obtained on precision part surfaces made of steel, cast iron, copper and its alloys, aluminum and its alloys, which can be used in various machine-building products.

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INFLUENCE OF PHYSICAL-MECHANICAL CHARACTERISTICS OF COMPOSITE RODS ON FRAME ASSEMBLY PROCESS PARAMETERS

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Many reinforced composite materials based on rod frames have been developed and their effectiveness has been proven. However, their wide application is hindered by the lack of scientifically well founded methods for selecting frame assembly process parameters.

In frames with hexagonal, transversely isotropic reinforcement systems the rods are placed in rows in the vertical and horizontal planes[1]. We shall refer to rods located in these planes as vertical and horizontal rods. The frame is assembled of rigid carbon-reinforced plastic rods of circular cross section with diameter d, manufactured by drawing and arriving for assembly in batches. Assembly of the frame is performed by longitudinal feeding of horizontal rods d^h between rows of vertical rods dv, preliminarily installed in apertures in the rigid assembly plate at a certain spacing t.

The purpose of this work is to establish the relationship between the physical-mechanical characteristics of the rods and such parameters of the assembly as the horizontal layer feed force, distance from lower horizontal layer to upper grid or horizontal feed height. Since in actual manufacturing conditions there is a certain rod diameter tolerance, the nature of the connection of a horizontal layer with a vertical layer is determined by the difference $t-(dh + d^v) = i$. Where $i \geq 0$ the rods meet with a certain gap, where $i \leq 0$ — with some interference. Meeting with interference results in contact and bending deformations of the rods, causing force of resistance Q_1. With high bending rigidity of the rods, force Q1 is made up of the forces N required to overcome the contact deformation of the rod material by the amount of the interference i. This case is characteristic when rods are fed right up to the assembled plate or the previous horizontal row. The force required in this case, as we know2, depends on the transverse elasticity modulus and Poisson's ratio of the rods which, in turn, are determined by the properties of the binder.

When the rods are fed in at some height above the point of contact with the vertical rods, the force of resistance Q_i consists of the forces of friction N at the contact points. The forces of friction of the rods arise due to the forces of normal pressure, resulting from bending of the rod by the interference i. The selection of interference in this case is based on bending deformations of the vertical rods and force N is determined from the following equation3:

$$N = \frac{48 E I_z f}{l^3\left(1+16\frac{E}{G}\frac{r^2}{l^2}\right)} \qquad (1)$$

where E and G are the elasticity and shear moduli of the rod;

f is the coefficient of friction; Iz = *πd4/64;*

r is the transverse cross-sectional radius;

l is the distance between the lower point of attachment of the vertical rod and the upper grid.

For assembly of the upper grid

$$N = \frac{3E I_z f}{l^3\left(1+4\frac{E}{G}\frac{r^2}{l^2}\right)} i \qquad (2)$$

where l is the feed height of the horizontal layer.

The condition of loading of the horizontal rod as a layer is pushed in indicates that the strength of the rod allows us to determine from (1) or (2) the optimal value of l for each version.

Thus, the equation N = f(i) can be obtained by computation for each type of deformation.

Calculation of the value of i requires that we study the distribution of rod diameters. We know that the statistics of the distribution of rod diameter in a batch follows the normal distribution4. Since selection of rods from a batch for installation in vertical rows is a random process, while the size of a batch is large, the distribution of rod diameters in rows follows the same rule. Thus, for a given horizontal rod dh we can find the limit of values of vertical rod diameters in contact with interference: dvmin = $t\text{-}d^h_i$ and dhmax. After determining the number of vertical rods nv for a given dhi we can obtain the equation N = f(dhi). Representing $d^h = x$, $d^v = y$, we obtain the equation for calculation of the resistance

$$Q_i = n^v \int_{d^v_{min}}^{d^v_{max}} N(x)\varphi(x)dx \qquad (3)$$

for the resistance to movement of all rods in a horizontal row which are fed in at the same time:

$$Q = \int_{d_{min}}^{d_{max}} N^*(x)\varphi(x)c \qquad (4)$$

where N* is the value of function N(x) where d^h = *π/e(d^h)*,

π/e(d) is the median of the distribution.

The values obtained from equation (3) are used to estimate the sufficiency of strength of a rod, while equation (4) is used in calculation of the required assembly device feed unit drive power.

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DETERMINATION OF OPTIMAL SPIRAL REINFORCEMENT PROCESS PARAMETERS CONSIDERING MECHANICAL BEHAVIOR

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The need to decrease the mass of structures while retaining their load-bearing capacity has led to extensive utilization in technology of rod elements of various profiles made of composite materials both as load-bearing and as attachment elements. To increase the load-bearing capacity, rod elements are designed so as to implement a longitudinal-transverse reinforcement scheme. This is usually done by introducing fabric interlayers to the structure of the material or one or more transversely wound layers.

The semifinished product used in the manufacture of rods of this structure is a hollow tube consisting of one or more spirally wound coaxial layers of basic reinforcement. The profile form of this tube may be rectangular, *I*-shaped or some other transverse cross section.

The process used to produce a coaxially reinforced semifinished product differs from standard processes used with unidirectional fiber materials in that the operation of spiral winding is included. This results in a number of specific features both of the implementation of the process and of the computation of its parameters.

As the spirally reinforced semifinished product is produced, the moment created by the tension on the winding filament causes the main reinforcement to bend by a certain angle which depends on the location of the fiber relative to the center of the product, the type of main reinforcement, as well as the dimensions of the product being manufactured. The presence of curved fibers in the composite structure decreases the strength and elastic characteristics of the product. Curvature of the fibers is particularly dangerous for rod products working in compression, since the presence of layers with lower strength significantly reduces the critical failure load.

It is therefore necessary in the manufacture of coaxially reinforced semifinished goods to implement a ratio of strength and process parameters such that the curvature of the cords or fibers of the main reinforcement is minimized.

By limiting the maximum permissible deflection angle of the main reinforcing material, we can compute the maximum ratio of forces of application of the main and secondary reinforcement for each coaxial labor. Thus, for two coaxial labors

$$\frac{T_{H1}}{P_0} \leq \frac{n_1 K_1 [\gamma]}{2}\left(1 + \frac{R_1}{R_2}\right) \qquad (1)$$

$$\frac{T_{H2}}{P_0} \leq 2[\gamma]K_2\left[\frac{n_1 R_1}{3R_2}\left(1 + \frac{R_1}{4R_2}\right) + \frac{n_2}{2}\left(1 + \frac{R_1^2}{R_2^2}\right)\right. \qquad (2)$$

T_{h1}, T_{h2}, n_1, n_2, R_1 and R_2 are the tension on the winding filaments, number of cords of main reinforcement and radius of the spiral winding of coaxial layers 1 and 2;

P0 is the tension on one cord of the main reinforcement;

$[\gamma]$ is the maximum permissible deflection of the main reinforcement;

k_1, k_2 are correction coefficients considering the filling of the semifinished product for layers 1 and 2.

During layup of the spiral layers of secondary reinforcement, the product performs forced oscillations, which can damage the fiber reinforcement against the support, distort the spacing of the spiral winding and thus reduce the mechanical characteristics of the product. These phenomena can be prevented by calculating the relationship of force and structural parameters of the process and the equipment which implements it such that oscillating amplitude of the product does not exceed the maximum value of [y].

By assigning the maximum permissible amplitude of oscillation [y], and using the calculated values of T_{Hi} defined in (1) and (2) from the condition of untwisted cords of main reinforcement, we can find the range of values of winder rotation speed such that resonant phenomena do not occur:

$$\omega \leq \sqrt{p^2 - \frac{T_H\, X(c) \cdot X \cdot p}{\mathcal{P}[y]\left(\frac{EJ}{KG} J_2 - FJ_1\right)}} \qquad (3)$$

where x is the normal oscillating function; x(c) is its value at the point of application of the perturbing force.

Thus, analysis of the process of manufacturing spirally reinforced semifinished products has yielded equations for calculation of the major parameters of the process.

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OPTIMIZATION OF PROCESS OF MANUFACTURING MULTILAYER COMPOSITE ELECTRICALLY CONDUCTING STRUCTURES

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Thick-film composite electrically conducting structures are cerametallic compounds consisting of a glass and a conducting phase1, 2.

Mathematical modeling and optimization of the manufacturing process of thick-film electrically conducting structures is a pressing task of modern microelectronics.

In this work, methods of nonequilibrium thermodynamics are used to obtain equations for the transfer of energy and matter, describing the processes of printing, drying and firing of electrically conducted pastes.

The paste is described by a model of a thixotropic liquid, the viscosity of which is a function of the shear stresses and deformation rates.

Based on an operator method equations are produced for a thixotropic electrically conducting paste allowing determination of the distribution of pressure of the paste beneath a blade.

One particular case of the equations constructed is represented by the Reynolds equation describing the distribution of pressure of a Newtonian fluid.

The matrix is an orthotropic grid plate, over the surface of which a blade moves at a certain speed and inclination, applying the paste to the ceramic substrate in the form of rectangular thick films of various dimensions.

Equations are derived for the rate of movement of the blade, dimensions of the matrix, force acting on the blade, tensile force on the filaments of the matrix and their influence on the quality of printing thick-film electrically conducting structures.

Equations for design of the operation of drying and firing were produced using:

1) balance equations for the momentum of the three-component medium considering structural conversions and chemical reactions among the components of the structure;

2) mass balance equations;

3) equations for distribution of electrical potential in the composite;

4) balance relationships for production of entropy;

5) physical relationships describing the general rule of plastic flow.

The drying and firing technology were modeled by constructing the plasticity function

$$\frac{3}{2}\left[(\sigma_{ij} - \delta_{ij} p)^2 + \frac{3}{2} p^2 \frac{\theta}{1-\theta}\right] = (1-\theta)^3 \sigma_T^2 \quad (1)$$

here, $$p = \frac{\sigma_{11} + \sigma_{22} + \sigma_{33}}{3}$$

s_{ij} are the stress tensor components; θ is the porosity of the resistive structure body; σ€ is the plastic limit; δMIij is the Kronecker symbol.

The physical relationships were obtained from the rule of plastic flow. The compacting of the resistive structure was determined from the mass balance equation

$$-\frac{d\rho}{\rho} = d\varepsilon_{11} + d\varepsilon_{22} + d\varepsilon_{33} = \frac{d\theta}{1-\theta} \quad (2)$$

where ρ is the density of the material; ε_{ij} are the deformation tensor components.

The equation for computation of the conductivity of the layered composite electrically conducting structures is taken as

$$R = R_0(1+\alpha_R T) + \left\{R_1 \frac{\sin gT}{gT}\left(1+\exp\frac{E}{kT}\right)\right\} \,//\, R_2 \exp\left(\frac{T_0}{T}\right)^{1/n} \quad (3)$$

here the symbol || represents parallel connection of unit cells in the structure; R_0, R_1 and R_2 are quantities representing the metal, tunnel-barrier and jump mechanisms of conductivity in the structure, α_R is the temperature coefficient of resistance of the conducting phase, g is the width and height coefficient, E is the activation energy, which depends on the density of localized states and the length of exponential attenuation of the spherically symmetrical wave function of an electron.

As the criterion of optimality of the manufacturing process of a thick-film resistor, we utilize the functional

$$J = \iint_{V\,0}^{\tau} \left[(R-R^*)^2 + \alpha \bar{\sigma}^{ij} \bar{\dot{\varepsilon}}_{ij}\right] dV\, d\tau \quad (4)$$

where R* is the assigned resistance; $\bar{\sigma}^{ij}$, $\bar{\varepsilon}_{ij}$ are

the residual stresses and strains in the structure; α is the weight coefficient; τ is the time of the manufacturing process; V is the volume of the resistor.

The control function is the temperature of the external medium. Based on the criterion of optimality selected by the method of Lagrange factors, a conjugate system of equations was also obtained which, along with the initial system, allows optimization of the technological process, providing for the creation in a composite conducting structure of a resistance within the levels of tolerance and minimum residual stress.

Based on the calculations performed, optimal temperature profiles were constructed for the operations of drying and firing of resistive pastes as functions of time. Heating and cooling rates and holding times were computed for resistive structures to achieve the minimum of functional (4).

It is shown that the residual stress and strength of the structure are greatly influenced by the cooling rate. The dimensions of the structure are determined by shrinkage deformations, which are functions of density.

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USE OF MICROPOROUS METAL MATERIALS FOR ANTIFRICTION SURFACES IN CONTACT WITH WET MASSES

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The creation of operating surfaces with low friction and adhesion is quite important for the design of earth moving, reclamation, soil working and many other types of machines operating under moist conditions when adhesion and attachment of moist masses to working surfaces by freezing make processes more difficult or impossible.

One of the most promising trends in the solution of this problem is the use of microporous metal composite materials obtained in sheet form by powder metallurgy methods. The operating surfaces of these machines (buckets, blades, beds) are quite large (up to 1-5 m). Practical problems therefore arise in the use of microporous sheet materials of low strength and in the assurance of good penetration of lubricating fluids or gases through them for the creation of an intermediate adhesive layer between the working surface and the material being worked.

The use of microporous working surfaces of composite materials assures uniformity of consumption and distribution of the lubricating fluid in the plane of contact with the dispersed material (soil, cement-concrete mixture, asphalt, et cetera). A ladle using a microporous antiadhesive coating has been developed and tested (author's certificate number 394507).

Within the ladle, a microporous material about 5-6 mm thick is applied on corrugated projections, so that a cavity 5-10 mm deep is left for the flow of the lubricating fluid between the outer wall and the microporous layer. At some points the gap between them is closed by solid barriers in order to produce closed cavities with various liquid or gas feed pressures, depending on the distribution of external pressure of the mass over the length of the working surface. The fluid can be fed by a water pump using capillary flow through microscopic pores.

Experiments have been conducted on the effectiveness of microporous surfaces in construction processes. The working surface was made as a sheet with a cavity thickness of 5 mm. The microporous surfaces were sheets 4 mm thick made by pressing of iron powder (98%) on a nickel binder (4%) and titanium. The porosity of the material was 35%, pore size 2-4 microns.

Water containing a surfactant and mineral oil diluted with kerosene were tested as lubricating fluids. The decrease in forces of friction and adhesion were estimated, as well as the need for additional pressure to provide the necessary lubricating layer thickness Δ. Experiments determined that the value of Δ = 10-15 μm. The use of microporous surfaces as removable or permanent shields supports complete dumping of moist masses which adhere or freeze to the ladles and blades of earthmoving machines and transportation equipment. Liquid lubrication requires 5-10 times less energy than gas lubrication. Iron-based materials corrode in water, plugging the pores. For use under these conditions, noncorroding materials or hydrocarbon-based fluids should be used. Addition of 0.5-1% surfactant and an additional 103-104 pascals (by changing the height of the container of liquid relative to the working surface) increases the capillary flow.

Due to the comparatively low strength of pressed microporous materials, the working surfaces should rest on projections (corrugations) with distances between them of 100-150 mm. The flow can be automatically regulated by sensors to assure that the feed pressure is slightly higher than the pressure of the mass on the working surface. By decreasing the contact of the surface with the soil (due to the liquid or gas layer formed), these devices greatly reduce friction and adhesion, as well as wear, allowing materials with lower wear resistance to be used.

V. INFORMATION SUPPORT OF CREATION OF PRODUCTS OF COMPOSITE MATERIALS

UDC 620.22-419.002.6

THE "DAUPHINE" TASK-ORIENTED INFORMATION SYSTEM

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Information support of scientific research is an important component of work on the creation of products of composites. Information support is usually performed in two modes: 1) supply of scientific information documents to designers; and 2) supply of data retrieval services. The tremendous flow of scientific and technical information makes the development of means for automating information activities quite pressing.

The "DAUPHINE" automated information system has been created at the Institute of Mechanics Problems, Ukrainian Academy of Sciences, and has been in full use for eight years. The system is a task-oriented one and supports scientific and technical developments in the area of powder metallurgy, composite materials, powder coatings and new ceramics. The information is output in the form of machine reports containing full bibliographies and abstracts of all open-source publications available in the USSR: scientific articles, monographs, authors' certificates, patents, dissertations, reports of scientific research and development work, et cetera. The source of secondary documents input to the data base consists of 17 issues of the National institute of Scientific and Technical Information abstract journals, 22 abstract journals of VNIIPI, 2 abstract journals of the National Scientific and Technical Information Center, 4 abstract journals of the National Scientific Research Institute of Inter-Industry Information, as well as the foreign abstract journals Chemical Abstracts and STAR, plus technical and promotional documentation supplied by some 2,500 foreign firms operating in the areas of interest to the information system.

The input stream of the system is over 12,000 documents per year. It serves some 60 departments of the Institute and 100 external organizations in the USSR with an average of 450 constant profiles (IRI mode with monthly reports) and undertakes 50-60 searches per year in RETRO mode (searching the entire data file consisting of 75,000 documents on magnetic media [as of January, 1989]).

The logic and semantic support of the DAUPHINE system is based on a lexicon organized as a hierarchical-network structure (multidimensional thesaurus). The information-retrieval language, which contains some 2000 lexical units with intelligent precoordination, has a well developed grammatical apparatus — indicators of role (morphology) and relationship (syntax). The software of the system is the "context" original program complex, intended for use on YeS computers of model 1020 and higher. The system operates in both batch and dialog mode. The information retrieval language, software system and detailed indexing rules support operation of the system with very high ratings of relevance and completeness of output in response to any unpredictable request.

Given the present version of the system, searches can be conduced by author, firm name, brand name, source of publications, et cetera. In the near future the system will support searches by material, product, equipment used, etc.

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STRUCTURE OF INFORMATION SUPPORT FOR CAD OF COMPOSITE MATERIAL PRODUCTS

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The great complexity and cumbersomeness of the process of designing composite material products and developing processes for their manufacture require the use of powerful scientific and technical facilities and methods capable of speeding up the design process. Very important in this process are computer-aided design (CAD) systems.

One of the most important subsystems of a CAD system is its information support subsystem, based on automated data bases. The information contained in these data bases must be properly structured and must satisfy the demands of completeness and reliability, while the data base management system must provide the user with rapid and easy access to the information. As a rule, CAD systems are man-machine systems in which individual decisions are made by various types of designers working with the automated data base and using heuristic methods and expert estimates. Another portion of the operations (such as engineering computations) may be performed by the computer automatically. The design process for composite material products usually involves large numbers of different specialists (designers, mechanical engineers, technological process experts, materials, scientists), and it is therefore quite important to develop efficient organization of the CAD system information support, the major task of which is effective satisfaction of the information needs of various types of designers and individual components of the CAD system.

This work studies the structure of a CAD information support system for composite material products, considering the peculiarities of the process of designing composite material products. A conceptual model of a data base and thesaurus of the subject area — technical materials — have been developed.

The basis of the information support system is an automated data retrieval system containing a number of data bases: 1) properties of initial components used in composite materials; 2) properties of process materials (such as explosives, et cetera); 3) mathematical models of composite material properties; 4) models of typical composite material processes.

The automated data base can be utilized in three modes: 1) response to any unpredictable user query formulated in terms of the thesaurus; 2) response to standard queries of individual groups of specialists formulated in a near-natural query language; 3) automated input of data to application programs. Mode 1 is used for information support of the design process primarily in the stage of qualitative design of composite material products. Its end user is most frequently the chief designer's group. Mode 2 is generally used in the stage of parameter design. Its end users are the individual narrow-range specialists (materials scientists, technologists, et cetera). The end users of mode 3 are the application programs used for engineering computations. This mode is only used in the parameter design stage.

As an example, the information support system of a CAD system for metal composite products and pulse technologies for their manufacture developed for an SM 1420 computer is studied.

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